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ARTICLE

Cost-Effective Strategies for the Prevention and Management of Diabetes Mellitus and Diabetic Retinopathy: A Comprehensive Review

Maduabuchukwu Innocent Nkollo[1,*], Nnaemeka Alvand Onwukwe[2], Edafe Oghenegangan Emurotu[1], Bobby Ikponmwosa Ebuehi[1], John Esimaje Moyegbone[3], Prisca Onyema[4], Anita Ayovunefe[1], Helen Omonigho Lucky-Udi[1], Ayodeji Ezekiel Ige[5], Aghogho Odogu[6], Franklin Ehigiator Kio[6]

[1] *Department of Optometry and Vision Science, Faculty of Allied Medical Sciences, Dennis Osadebay University, Anwai, Asaba, Delta State, Nigeria.*

[2] *Department of Optometry, Faculty of Health Sciences and Technology, David Umahi Federal University of Health Sciences, Uburu, Ebonyi State, Nigeria.*

[3]*Department of Environmental and Public Health Optometry, Faculty of Optometry, University of Benin, Benin-City, Edo State, Nigeria.*

[4] *Department of Optometry, Faculty of Allied Health Sciences, Bingham University, Karu, Nassarawa State, Nigeria.*

[5] *Department of Optometry and Vision Science, Faculty of Life Sciences, University of Ilorin, Ilorin, Kwara State, Nigeria.*

[6]*Department of Optometry, College of Medical and Health Sciences, Novena University, Ogume, Delta State, Nigeria.*

*Corresponding author: Dr. Maduabuchukwu Innocent Nkollo. Email: nkolloinnocent@gmail.com

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Abstract

Diabetes mellitus and diabetic retinopathy represent major global public health challenges associated with significant morbidity, visual impairment, mortality, and economic burden. Diabetic retinopathy, a leading microvascular complication of diabetes mellitus, remains one of the primary causes of preventable blindness among working-age adults worldwide. The increasing prevalence of diabetes, particularly in low- and middle-income countries, has intensified the need for cost-effective preventive and management strategies capable of reducing disease progression, healthcare expenditure, and visual disability. This review aimed to evaluate current cost-effective strategies employed in the prevention, screening, and management of diabetes mellitus and diabetic retinopathy.

Relevant literature was obtained from electronic databases including PubMed, Scopus, Google Scholar, ScienceDirect, and ResearchGate using keywords related to diabetes mellitus, diabetic retinopathy, cost-effectiveness, prevention, screening, teleophthalmology, and healthcare economics. Evidence from peer-reviewed articles, clinical trials, guidelines, and systematic reviews was critically analyzed.

Findings from the review indicate that preventive healthcare approaches such as lifestyle modification, glycaemic control, blood pressure and lipid management, patient education, and routine retinal screening significantly reduce the incidence and progression of diabetic retinopathy while lowering long-term healthcare costs. Technological innovations including teleophthalmology, artificial intelligence-assisted retinal screening, and portable retinal imaging systems have further improved accessibility, efficiency, and affordability of diabetic eye care services. Despite these advances, challenges such as poor awareness, inadequate healthcare infrastructure, high treatment costs, and limited specialist availability continue to

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affect effective disease management.

In conclusion, investment in preventive care, early detection, integrated healthcare delivery, and affordable screening technologies remains essential for reducing blindness, improving patient outcomes, and minimizing the economic burden associated with diabetes mellitus and diabetic retinopathy.

Keywords: Diabetes Mellitus; Diabetic Retinopathy; Cost-Effectiveness; Retinal Screening; Teleophthalmology.

1. INTRODUCTION

Diabetes mellitus (DM) is one of the most significant non-communicable diseases affecting global public health, with a rapidly increasing prevalence across both developed and developing nations [1]. Characterized by chronic hyperglycaemia resulting from defects in insulin secretion, insulin action, or both, diabetes is associated with numerous systemic complications that contribute substantially to morbidity, mortality, and healthcare expenditure. According to the International Diabetes Federation [2], hundreds of millions of people worldwide currently live with diabetes, and this number is projected to rise considerably in the coming decades due to urbanization, sedentary lifestyles, obesity, population aging, and unhealthy dietary habits. The disease places a significant socioeconomic burden on individuals, healthcare systems, and governments, particularly in low- and middle-income countries where access to healthcare resources remains limited [3].

Among the various complications of DM, diabetic retinopathy (DR) remains one of the most common and vision-threatening microvascular complications. DR is characterized by progressive retinal vascular damage resulting from prolonged hyperglycaemia and is a leading cause of preventable blindness among working-age adults globally. The condition often progresses silently in its early stages, with many patients remaining asymptomatic until irreversible visual impairment develops [4]. In addition to reducing quality of life, visual disability caused by DR contributes significantly to productivity loss, increased dependency, and escalating healthcare costs [5].

The growing prevalence of DM and DR has intensified the need for effective and economically sustainable healthcare strategies. Although substantial advances have been made in the diagnosis, monitoring, and treatment of both conditions—including pharmacological therapy, laser photocoagulation, intravitreal anti-vascular endothelial growth factor (anti-VEGF) injections, retinal imaging technologies, and lifestyle interventions—the financial burden associated with long-term disease management remains considerable [6]. In many healthcare settings, especially resource-constrained environments, the high cost of treatment and inadequate access to specialized eye care services hinder optimal disease control and timely intervention [7]

Cost-effective healthcare strategies have therefore emerged as an essential component in the prevention and management of DM and DR. Cost-effectiveness in healthcare refers to interventions that provide optimal clinical outcomes while minimizing financial expenditure and resource utilization. Preventive approaches such as early screening, patient education, glycaemic control, lifestyle modification, teleophthalmology, and community-based healthcare programs have demonstrated significant potential in reducing disease progression, visual impairment, and overall healthcare costs [8]. Furthermore, advances in digital retinal imaging, artificial intelligence-assisted screening systems, and integrated diabetes care models may improve accessibility and affordability of diabetic eye care services, particularly in underserved populations [9].

Understanding the economic implications of diabetes care is critical for policymakers, clinicians, researchers, and healthcare administrators in designing sustainable healthcare systems capable of managing the increasing disease burden. Evaluating the cost-effectiveness of various preventive and

therapeutic interventions can help optimize resource allocation, improve patient outcomes, and reduce the long-term economic impact associated with diabetes-related complications.

Therefore, this comprehensive review aims to examine the cost-effective strategies currently employed in the prevention and management of DM and DR. The review further explores the economic burden of these conditions, evaluates existing therapeutic and screening approaches, and highlights emerging innovations that may enhance the accessibility, efficiency, and affordability of diabetes and DR care globally.

2. METHODOLOGY

This study was conducted as a comprehensive narrative review with the aim of evaluating cost-effective strategies employed in the prevention and management of DM and DR. Relevant literature was systematically searched and critically reviewed to provide current evidence on the economic and clinical effectiveness of various preventive, diagnostic, and therapeutic interventions associated with both conditions. Generative AI was used for data search, correction of grammar and ensure the right research language is used.

2.1. Literature Search Strategy

A comprehensive electronic search of scientific databases was performed using databases including Google Scholar, PubMed, Scopus, ScienceDirect, and ResearchGate. Published articles, review papers, clinical studies, guidelines, and reports related to diabetes mellitus, diabetic retinopathy, healthcare economics, and cost-effective management strategies were retrieved.

The search was conducted using combinations of relevant keywords and Medical Subject Headings (MeSH) terms, including: “Diabetes Mellitus,” “Diabetic Retinopathy,” “Cost-effectiveness,” “Economic burden,” “Prevention,” “Management,” “Screening,” “Teleophthalmology,” “Anti-VEGF therapy,” “Lifestyle intervention,” and “Healthcare costs.” Boolean operators such as AND, OR, and NOT were employed to refine and optimize the search results.

2.2. Inclusion and Exclusion Criteria

Articles included in this review were:

- Published in English language;
- Peer-reviewed;
- Focused on DM and/or DR;
- Addressed preventive, diagnostic, therapeutic, or economic aspects of disease management;
- Published within the last 10-15 years to ensure current and relevant evidence.

Studies were excluded if they were duplicate publications, lacked sufficient methodological detail, were unrelated to cost-effective strategies or economic evaluation, consisted solely of conference abstracts without full-text availability.

2.3. Data Extraction and Analysis

Relevant data were extracted from selected studies and organized according to study objectives, methodology, intervention type, outcomes, and major findings. Particular attention was given to interventions demonstrating clinical efficacy alongside reduced healthcare expenditure or improved resource utilization.

The extracted information was subsequently grouped into thematic areas, including prevention and lifestyle modification, glycaemic control strategies, screening and early detection of DR, pharmacological and surgical interventions, telemedicine and artificial intelligence applications, and public health and community-based approaches.

A qualitative synthesis of findings was performed to compare the effectiveness, accessibility, and economic implications of various management strategies. Emphasis was placed on interventions applicable to low- and middle-income countries where healthcare resources are often limited.

3. ECONOMIC BURDEN OF DM AND DR

The economic burden associated with DM and DR is enormous and continues to rise globally due to increasing disease prevalence, prolonged life expectancy, urbanization, and lifestyle changes [10]. The chronic nature of diabetes requires lifelong monitoring and continuous medical care, thereby placing substantial pressure on healthcare systems, governments, caregivers, and patients. The financial impact extends beyond direct medical costs to include indirect costs such as loss of productivity, reduced quality of life, disability, premature mortality, and caregiver expenses [11].

DR further compounds this burden because visual impairment often results in unemployment, dependency, psychological distress, and increased healthcare utilization [12]. In many developing countries, late presentation of diabetic complications due to poverty, poor awareness, and inadequate healthcare access significantly increases treatment costs and worsens patient outcomes [13].

The economic burden can be categorized into several major components including hospitalization, medications, laboratory investigations, retinal imaging, surgical procedures, and follow-up care.

3.1. Hospitalization

Hospitalization constitutes one of the largest contributors to the economic burden of DM and DR [14]. Patients with poorly controlled diabetes frequently require hospital admission due to acute and chronic complications such as diabetic ketoacidosis, hyperosmolar hyperglycaemic state, severe hypoglycaemia, cardiovascular diseases, diabetic foot ulcers, nephropathy, stroke, and severe ocular complications [15].

Hospital admission costs are often high because they involve bed occupancy charges, emergency care services, intensive care unit (ICU) management, physician consultation fees, nursing care, medication administration, diagnostic procedures, surgical interventions and rehabilitation services.

In patients with DR, hospitalization may become necessary when complications such as vitreous hemorrhage, retinal detachment, neovascular glaucoma, or severe diabetic macular edema occur [15,16]. These advanced conditions often require multidisciplinary care involving ophthalmologists, endocrinologists, optometrists, internists, and surgeons, thereby increasing treatment costs.

Frequent hospital admissions also contribute to indirect financial losses due to loss of income, absence from work, reduced productivity, transportation expenses, and caregiver burden.

In low-income settings where health insurance coverage is limited, many patients pay out-of-pocket for hospitalization, resulting in catastrophic healthcare expenditure and financial hardship [16]. Consequently, preventive measures such as early diagnosis, glycaemic control, lifestyle modification, and routine retinal screening are considerably more cost-effective than recurrent hospitalization for advanced disease complications.

3.2. Medications

Medication costs represent another major component of diabetes-related healthcare expenditure. Since DM is a lifelong disease, patients often require continuous pharmacological therapy for glycaemic control as well as treatment of associated comorbidities and complications [6].

Common medications used in diabetes management include insulin preparations, metformin, sulfonylureas, DPP-4 inhibitors, SGLT2 inhibitors, GLP-1 receptor agonists, antihypertensive drugs, lipid-lowering agents and antiplatelet drugs.

The cumulative cost of these medications can be substantial, especially when multiple drug combinations are required. Newer antidiabetic agents, although effective, are often expensive and inaccessible to many patients in developing countries.

In DR management, pharmacological expenses increase further due to the use of intravitreal anti-vascular endothelial growth factor (anti-VEGF) agents such as:

- Bevacizumab
- Ranibizumab
- Aflibercept

These medications often require repeated injections over long periods, making treatment financially burdensome. Patients may require monthly or bimonthly injections, in addition to retinal imaging and specialist consultations [18].

Medication non-adherence resulting from high costs frequently leads to poor glycaemic control and disease progression, thereby increasing the likelihood of severe complications and hospitalization. Therefore, the use of affordable generic medications, biosimilars, government subsidies, and health insurance schemes can significantly reduce the economic burden associated with long-term pharmacotherapy [19].

3.3. Laboratory Investigations

Laboratory investigations are essential in the diagnosis, monitoring, and management of DM and its complications. Although individually some tests may appear inexpensive, the cumulative cost over a patient's lifetime becomes substantial due to the chronic nature of the disease [20].

Routine laboratory investigations commonly performed in diabetic patients include:

- Fasting blood glucose
- Random blood glucose
- Oral glucose tolerance test
- Glycated hemoglobin (HbA1c)
- Lipid profile
- Kidney function tests
- Urinalysis
- Microalbuminuria testing
- Liver function tests
- Electrolyte assessment

HbA1c testing is particularly important because it provides information about long-term glycaemic control and helps guide treatment decisions. However, repeated HbA1c testing every 2-3 months may become financially challenging for many patients in low-resource settings [21].

Patients with DR may also require additional investigations to assess systemic disease progression and risk factors associated with retinal damage [20]. Repeated laboratory monitoring contributes significantly to healthcare expenditure, especially in healthcare systems lacking adequate insurance coverage. Limited access to affordable laboratory services often leads to delayed diagnosis and poor disease monitoring, which may ultimately increase long-term treatment costs due to preventable complications. Investment in low-cost diagnostic technologies, community screening programs, and subsidized laboratory services may improve early disease detection while reducing the financial burden associated with advanced complications [22].

3.4. Retinal Imaging

Retinal imaging plays a central role in the screening, diagnosis, monitoring, and treatment planning of DR. However, the cost of retinal imaging equipment, maintenance, specialist interpretation, and repeated examinations contributes substantially to the economic burden of diabetic eye care.

Common retinal imaging modalities include fundus photography, optical coherence tomography (OCT), fluorescein angiography, fundus autofluorescence imaging and OCT angiography.

OCT is particularly useful in detecting diabetic macular edema and monitoring response to treatment. However, OCT machines are expensive to acquire and maintain, making access difficult in many developing countries [23]. Patients undergoing anti-VEGF therapy often require repeated retinal imaging during follow-up visits to evaluate disease progression and treatment response. This repetitive monitoring increases cumulative healthcare costs significantly [24].

In rural and underserved communities, lack of retinal imaging facilities contributes to delayed diagnosis and increased prevalence of preventable blindness. To address this challenge, cost-effective alternatives such as portable retinal cameras, smartphone-based fundus photography, and teleophthalmology have been introduced [25]. These technologies reduce transportation costs, improve accessibility, and enhance early detection of DR.

Artificial intelligence-assisted retinal screening systems may further reduce costs by minimizing dependence on specialist interpretation while improving screening efficiency [24,45].

3.5. Surgical Procedures

Surgical procedures for advanced diabetic complications contribute significantly to healthcare expenditure. In DR, surgery is often required when irreversible retinal damage or vision-threatening complications develop.

Common ophthalmic surgical procedures include:

- Vitrectomy
- Retinal detachment repair
- Cataract surgery
- Glaucoma surgery
- Laser photocoagulation [25]

Vitrectomy is one of the most expensive procedures in diabetic eye care because it requires:

- Specialized vitreoretinal surgical equipment
- Highly trained surgeons
- Operating theatre facilities
- Postoperative medications
- Extended follow-up care [26]

Patients with proliferative DR complicated by vitreous hemorrhage or tractional retinal detachment often require vitrectomy to preserve vision. However, surgery is usually more expensive than preventive interventions such as regular screening and early laser therapy [25].

Diabetes also increases the risk of cataract formation, necessitating cataract surgery at earlier ages. Furthermore, poor wound healing and increased risk of postoperative infection in diabetic patients may increase treatment complexity and costs.

Laser photocoagulation remains relatively cost-effective compared to repeated intravitreal injections and advanced surgical interventions. Early treatment through laser therapy may prevent progression to severe disease requiring costly surgery [6].

The financial burden of surgery is particularly devastating in low-resource settings where patients frequently lack insurance coverage and specialized ophthalmic facilities are scarce [27]

3.6. Follow-Up Care

Follow-up care is an essential aspect of DM and DR management because both conditions require lifelong monitoring. Continuous follow-up helps evaluate treatment effectiveness, monitor disease progression, detect complications early, and reinforce patient compliance [28]

Follow-up care may involve:

- Routine clinical consultations
- Blood glucose monitoring
- HbA1c testing
- Blood pressure assessment
- Retinal examinations
- Medication adjustments
- Lifestyle counseling
- Imaging studies
- Post-treatment monitoring [29]

Patients receiving anti-VEGF injections require frequent follow-up visits to determine treatment response and need for reinjection. Similarly, patients who undergo laser therapy or vitreoretinal surgery require long-term ophthalmic evaluation.

The cumulative cost of repeated hospital visits, transportation, consultation fees, diagnostic tests, and medications creates a substantial economic burden, especially for elderly patients and individuals living in remote areas.

Poor follow-up compliance is common among diabetic patients due to financial constraints, poor awareness, transportation difficulties, and limited healthcare accessibility. This often results in delayed detection of complications and poorer visual outcomes [28,29]

Cost-effective follow-up strategies such as:

- Telemedicine
- Community outreach programs
- Mobile eye clinics
- Integrated diabetic care services
- Digital health monitoring systems [29]

Can significantly reduce healthcare costs while improving patient adherence and clinical outcomes.

Ultimately, preventive care, patient education, and early intervention remain more economically sustainable than managing advanced diabetic complications requiring extensive follow-up and rehabilitation [30].

4. COST-EFFECTIVE STRATEGIES IN THE PREVENTION OF DM AND DR

Preventive healthcare strategies remain the most economically sustainable approach in reducing the global burden of DM and DR. Prevention not only minimizes disease incidence and progression but also reduces healthcare expenditure associated with hospitalization, medications, surgery, visual rehabilitation, and loss of productivity. Because diabetes is a chronic disease with lifelong implications, interventions aimed at preventing complications are considerably more cost-effective than treating advanced disease.

Several preventive strategies have proven effective in reducing the incidence and progression of DM and DR, particularly lifestyle modification and health education, glycaemic control, and blood pressure and lipid control [31].

4.1. Lifestyle Modification and Health Education

Lifestyle modification is one of the most effective and affordable strategies in the prevention and management of DM and DR. Unhealthy lifestyle behaviors such as physical inactivity, unhealthy diet, obesity, smoking, excessive alcohol consumption, and chronic stress significantly contribute to the development and progression of Type 2 DM and its complications.

Lifestyle intervention programs are considered highly cost-effective because they reduce dependence on expensive medications, minimize complications, and improve overall health outcomes [32].

4.1.1. Dietary Modification

Healthy dietary practices play a central role in diabetes prevention and control. Diets rich in fruits, vegetables, whole grains, legumes, and lean proteins help improve insulin sensitivity and maintain optimal blood glucose levels. Conversely, excessive intake of refined carbohydrates, saturated fats, sugary beverages, and processed foods contributes to obesity and insulin resistance.

Nutritional counseling encourages patients to reduce caloric intake, limit sugar consumption, increase dietary fiber intake, consume balanced meals, control portion sizes and reduce salt and unhealthy fat intake. Cost-effective nutritional interventions can significantly lower the risk of diabetic complications and reduce long-term healthcare costs. Community nutrition education programs are especially beneficial in low-resource settings where access to specialized diabetic care may be limited [32].

4.1.2. Physical Activity and Exercise

Regular physical activity improves glucose metabolism, promotes weight loss, enhances cardiovascular health, and increases insulin sensitivity [34]. Exercise also contributes to improved blood circulation and reduced systemic inflammation, thereby lowering the risk of DR progression.

Recommended physical activities include, walking, jogging, cycling, swimming, aerobic exercises and resistance training.

Exercise is one of the most affordable preventive strategies because it requires minimal financial investment while offering substantial health benefits. Regular physical activity reduces the likelihood of obesity, hypertension, dyslipidaemia, and cardiovascular diseases, all of which are major risk factors for diabetes and diabetic retinopathy.

Additionally, exercise reduces healthcare expenditure by decreasing the frequency of hospitalization and need for intensive pharmacological interventions [30].

4.1.3. Weight Management

Obesity is strongly associated with insulin resistance and Type 2 DM. Weight reduction through proper diet and exercise significantly lowers the risk of developing diabetes and delays disease progression in already diagnosed individuals.

Even modest weight loss can:

- Improve glycaemic control
- Reduce blood pressure
- Improve lipid profile
- Lower cardiovascular risk
- Reduce retinal vascular damage

Weight management programs are highly cost-effective because they prevent complications that would otherwise require expensive long-term treatment [22].

4.1.4 Smoking Cessation and Alcohol Reduction

Smoking contributes to vascular dysfunction, oxidative stress, and inflammation, thereby worsening diabetic complications including DR [27]. Excessive alcohol intake also negatively affects glucose metabolism and increases cardiovascular risk.

Smoking cessation and reduction of alcohol consumption:

- Improve vascular health
- Enhance treatment outcomes
- Reduce disease progression

- Lower healthcare costs

Public health campaigns promoting smoking cessation are inexpensive relative to the economic burden of advanced diabetic complications [32]. Health education is a fundamental preventive strategy in diabetes care. Patient awareness and understanding significantly influence disease outcomes, treatment adherence, and lifestyle choices [30].

Effective health education programs provide information regarding:

- Causes and risk factors of diabetes
- Importance of glycaemic control
- Medication adherence
- Healthy dietary habits
- Physical activity
- Blood pressure control
- Regular eye examinations
- Foot care practices
- Early symptoms of complications

Health education empowers patients to actively participate in disease management and make informed healthcare decisions. Improved patient awareness promotes early presentation, regular screening, and better compliance with treatment regimens.

Community outreach programs, school-based campaigns, media awareness initiatives, and primary healthcare education are relatively inexpensive interventions capable of reaching large populations. Such programs are especially important in rural and underserved communities where awareness of DR remains poor.

Health education also reduces indirect economic burden by preventing disability, visual impairment, and productivity loss [30,37].

4.2. Glycaemic Control

Effective glycaemic control is one of the most important and evidence-based strategies for preventing diabetes-related complications, particularly DR. Chronic hyperglycaemia causes retinal microvascular damage through mechanisms involving oxidative stress, inflammation, endothelial dysfunction, and accumulation of advanced glycation end-products.

Maintaining optimal blood glucose levels significantly reduces the onset and progression of DR and other microvascular complications [37].

4.2.1 Importance of Glycaemic Monitoring

Routine monitoring of blood glucose and glycated hemoglobin (HbA1c) helps evaluate treatment effectiveness and guide therapeutic decisions. HbA1c provides information regarding long-term glycaemic control and is a strong predictor of diabetic complications. Good glycaemic control reduces retinal vascular damage, delays progression of DR, decreases hospitalization rates, lowers risk of nephropathy and neuropathy and reduces cardiovascular complications. Although continuous monitoring may involve some financial cost, it remains considerably more cost-effective than treating advanced diabetic complications requiring surgery or prolonged hospitalization [39].

4.3. Medication Adherence

Proper adherence to prescribed medications is essential for maintaining stable glycaemic levels. Poor adherence often results in fluctuating blood glucose levels and accelerated progression of DR.. Medication adherence may be improved through patient counseling, simplified treatment regimens, affordable medications, health insurance support and community pharmacy programs. Use of affordable generic antidiabetic drugs can significantly reduce treatment costs while maintaining therapeutic effectiveness [40]

4.4. Early Intervention

Early diagnosis and prompt initiation of treatment improve long-term outcomes and reduce healthcare expenditure. Individuals with pre-diabetes may prevent progression to overt diabetes through lifestyle interventions and early medical management.

Timely glycaemic control is particularly important because retinal damage occurring in DR is often irreversible once advanced stages develop [16].

4.5. Self-Monitoring and Digital Health Technologies

Self-monitoring of blood glucose allows patients to detect abnormal glucose levels early and make appropriate lifestyle or medication adjustments.

Emerging digital technologies such as mobile health applications, continuous glucose monitoring systems, telemedicine platforms and remote patient monitoring improve glycaemic management and patient compliance. Although some technologies may initially appear expensive, they often reduce long-term costs by preventing severe complications and reducing hospital admissions [48].

4.6. Blood Pressure and Lipid Control

Hypertension and dyslipidaemia are important risk factors for the development and progression of diabetic retinopathy. Effective control of blood pressure and serum lipid levels significantly reduces retinal vascular damage and cardiovascular complications.

Integrated management of glycaemia, blood pressure, and lipids is more cost-effective than treating complications after disease progression [44]

4.6.1. Blood Pressure Control

Hypertension accelerates retinal microvascular damage by increasing vascular permeability, endothelial dysfunction, and retinal ischemia. Elevated blood pressure is strongly associated with progression of DR and increased risk of visual impairment.

Effective blood pressure management involves lifestyle modification, salt restriction, weight reduction, physical activity and antihypertensive medications

Common antihypertensive drugs used in diabetic patients include:

- ACE inhibitors
- Angiotensin receptor blockers (ARBs)
- Calcium channel blockers
- Diuretics

Blood pressure control significantly reduces retinal hemorrhages, macular edema, cardiovascular complications, risk of stroke and kidney disease. Preventing these complications reduces hospitalization rates and overall healthcare costs [44,48].

4.6.2. Lipid Control

Dyslipidaemia contributes to retinal vascular leakage, hard exudate formation, and progression of diabetic macular edema. Elevated serum cholesterol and triglycerides are associated with worsening retinal pathology in diabetic patients. Lipid management strategies include dietary modification, weight reduction, physical exercise and Lipid-lowering medications such as statins.

Statins not only reduce cardiovascular risk but may also contribute to stabilization of retinal vascular damage. Good lipid control reduces the need for surgical interventions, frequency of retinal edema, risk of cardiovascular disease and healthcare expenditure associated with advanced complications [42]

4.7. Combined Risk Factor Management

Simultaneous management of blood glucose, blood pressure, and lipid levels provides superior clinical outcomes compared to isolated treatment approaches. Multifactorial intervention significantly

reduces disease progression, visual impairment, hospitalization, mortality and long-term healthcare costs. Integrated diabetic care models involving endocrinologists, ophthalmologists, optometrists, nutritionists, nurses, and primary healthcare providers improve treatment efficiency and cost-effectiveness. Ultimately, preventive strategies remain the most sustainable approach in reducing the growing global burden of DM and DR [49]

5. COST-EFFECTIVE SCREENING STRATEGIES FOR DR

Cost-effective screening strategies focus on identifying DR before irreversible retinal damage occurs. Early detection allows prompt initiation of treatment, thereby reducing visual impairment, improving quality of life, and decreasing the financial burden associated with advanced disease management [47].

5.1. Importance of Early Screening

Early screening is fundamental in DR prevention because many patients remain asymptomatic until severe retinal damage develops. Retinal microvascular abnormalities may progress silently for years before visual symptoms become noticeable.

Routine screening provides several economic and clinical benefits, including:

- Early detection of retinal changes
- Prevention of irreversible blindness
- Reduced need for complex surgical procedures
- Lower hospitalization rates
- Improved treatment outcomes
- Reduced long-term healthcare costs
- Preservation of productivity and quality of life

Numerous studies have shown that regular diabetic eye examinations significantly reduce the risk of severe visual loss. Screening programs are therefore more economical than managing late-stage complications associated with blindness and disability [55].

5.2. Fundus Examination and Dilated Ophthalmoscopy

Dilated fundus examination remains one of the traditional and widely used methods for DR screening. During examination, pharmacological dilation of the pupil allows detailed visualization of retinal structures and identification of microvascular abnormalities such as:

- Microaneurysms
- Retinal hemorrhages
- Hard exudates
- Cotton wool spots
- Neovascularization
- Macular edema

Direct ophthalmoscopy and indirect ophthalmoscopy are relatively inexpensive screening techniques that can be performed in both primary and specialized healthcare settings. These methods are particularly valuable in low-resource environments where advanced retinal imaging technologies may not be readily available [56].

Although dilated fundus examination depends heavily on examiner expertise, it remains a cost-effective method for identifying patients requiring further ophthalmic evaluation and treatment [52,53].

5.3. Fundus Photography

Fundus photography has become one of the most widely utilized screening tools for DR. Retinal photographs provide permanent documentation of retinal findings and allow comparison over time to monitor disease progression.

Advantages of fundus photography include non-invasive assessment, rapid image acquisition, improved screening efficiency, permanent record storage, easier patient follow-up and remote image interpretation. Digital fundus photography is highly cost-effective because it enables large-scale screening programs with fewer specialist personnel. Retinal images can be interpreted by ophthalmologists, optometrists, or trained graders, thereby reducing workload on eye care specialists [45]

Non-mydriatic fundus cameras, which do not require pharmacological pupil dilation, further improve patient convenience and screening efficiency. These cameras reduce examination time and increase patient acceptance, making them suitable for mass screening programs. However, acquisition and maintenance costs of fundus cameras may pose challenges in developing countries.

Despite this, long-term economic benefits outweigh the initial investment because early diagnosis prevents costly visual complications [44].

5.4. Optical Coherence Tomography (OCT)

OCT is an advanced retinal imaging modality that provides high-resolution cross-sectional images of retinal layers. OCT is particularly valuable for detecting and monitoring diabetic macular edema (DME), one of the major causes of vision loss in diabetic retinopathy.

OCT enables:

- Early detection of retinal thickening
- Quantification of macular edema
- Monitoring of treatment response
- Accurate treatment planning

Although OCT equipment is expensive, its ability to guide timely intervention improves treatment outcomes and reduces unnecessary procedures. Early detection of macular edema through OCT may prevent severe visual impairment and reduce the need for costly surgical interventions.

The cost-effectiveness of OCT increases when used selectively in patients with suspected macular involvement rather than as a universal screening tool [57].

5.5. Fluorescein Angiography

Fluorescein angiography is an important diagnostic procedure used to evaluate retinal blood flow and vascular integrity in DR. The technique involves intravenous administration of fluorescein dye followed by serial retinal photography.

Fluorescein angiography helps identify:

- Retinal ischemia
- Capillary non-perfusion
- Microaneurysms
- Neovascularization
- Macular leakage

Although highly informative, fluorescein angiography is relatively invasive and more expensive than routine fundus photography. Consequently, it is generally reserved for patients with advanced or complicated DR rather than for routine screening purposes.

Selective use of fluorescein angiography improves cost-effectiveness by limiting the procedure to cases requiring detailed vascular assessment [39,44,51]

5.6. Teleophthalmology

Teleophthalmology has emerged as one of the most innovative and cost-effective strategies for DR screening, particularly in underserved and rural communities where access to eye care specialists is limited [38].

Teleophthalmology involves remote acquisition of retinal images, electronic transmission of images and remote interpretation by specialists.

This approach significantly reduces barriers associated with:

- Geographic distance
- Transportation costs
- Shortage of specialists
- Delayed diagnosis
- Long waiting times

Teleophthalmology screening programs allow primary healthcare workers and trained technicians to capture retinal images using portable fundus cameras. The images are then evaluated remotely by ophthalmologists or retinal specialists. The benefits of teleophthalmology include increased screening coverage, early referral of high-risk patients, reduced patient travel expenses, improved access to care and lower healthcare system burden. Teleophthalmology is particularly valuable in low- and middle-income countries where ophthalmic services are concentrated in urban areas. By decentralizing diabetic eye screening services, teleophthalmology improves accessibility while minimizing healthcare costs [38,50]

5.7. Artificial Intelligence-Assisted Screening

Artificial intelligence (AI) has transformed DR screening through automated retinal image analysis. AI algorithms trained using large retinal image datasets can identify DR with high sensitivity and specificity.

AI-assisted systems can detect:

- Microaneurysms
- Hemorrhages
- Exudates
- Neovascularization
- DME

AI-based screening offers numerous economic advantages including reduced dependence on specialists, faster image interpretation, increased screening efficiency, lower labor costs, reduced diagnostic delays and scalability for large populations like India [45].

In resource-limited settings with few ophthalmologists, AI systems can substantially improve screening capacity while reducing healthcare expenditure. Automated screening also allows specialists to focus on patients requiring urgent treatment rather than routine image interpretation.

Despite high initial implementation costs, AI-assisted screening may become highly cost-effective over time due to improved efficiency and reduced manpower requirements [49]

5.8. Community-Based Screening Programs

Community-based screening programs are effective public health strategies aimed at increasing awareness and accessibility of DR screening services.

These programs may involve mobile eye clinics, outreach campaigns, screening camps, primary healthcare integration and school and workplace awareness initiatives [55]

Community screening programs are particularly important in rural and underserved populations where healthcare access is poor. Early identification of DR through community outreach reduces late presentation and prevents avoidable blindness.

Mobile screening units equipped with portable retinal cameras and trained personnel can reach remote communities at relatively low operational costs compared to establishing permanent specialized facilities.

Community-based approaches also improve health education and encourage regular eye examinations among diabetic patients [60].

5.9. Smartphone-Based Retinal Imaging

Advances in smartphone technology have led to the development of smartphone-based retinal imaging systems for DR screening. These systems use smartphone cameras combined with retinal imaging adapters to capture fundus photographs.

Advantages include low equipment cost, portability, ease of use, accessibility in remote settings, rapid image sharing and integration with telemedicine systems

Smartphone-based screening may significantly improve diabetic eye care in developing countries where conventional retinal imaging equipment is unavailable or unaffordable.

Although image quality may sometimes be inferior to conventional fundus cameras, smartphone retinal imaging remains highly valuable for preliminary screening and referral purposes [57].

5.10. Integration of Screening into Primary Healthcare

Integrating DR screening into primary healthcare systems is another highly cost-effective strategy.

Primary healthcare workers can be trained to:

- Identify high-risk patients
- Perform basic retinal screening
- Educate patients
- Facilitate referrals

This integration improves early diagnosis and reduces patient overload in tertiary healthcare facilities. Routine retinal screening during diabetes clinic visits also increases compliance and reduces missed appointments. Collaborative care involving endocrinologists, optometrists, ophthalmologists, nurses, and primary healthcare workers enhances healthcare efficiency and reduces fragmentation of diabetic care services [58].

5.11. Challenges Affecting Cost-Effective Screening

Despite advances in screening technologies, several challenges continue to limit the effectiveness of DR screening programs, including, poor patient awareness, high equipment costs, shortage of trained personnel, inadequate healthcare infrastructure, poor referral systems, limited health insurance coverage, geographic barriers and poor patient compliance.

In many developing countries, patients often seek care only after visual symptoms develop, resulting in delayed diagnosis and higher treatment costs.

Addressing these barriers requires, government support, increased healthcare funding, public awareness campaigns, training of healthcare workers, expansion of telemedicine services and subsidized screening programs [31,44].

5.12. Future Perspectives in DR Screening

Future screening strategies are expected to become increasingly technology-driven, portable, and accessible. Emerging innovations include, AI-integrated portable retinal cameras, Cloud-based image analysis, fully automated screening systems, wearable retinal imaging devices and expanded telemedicine networks. These innovations may further reduce healthcare costs while increasing screening coverage and early detection rates.

Ultimately, cost-effective DR screening strategies remain essential for preventing blindness, reducing healthcare expenditure, and improving quality of life among diabetic patients worldwide.

6. RECOMMENDATIONS

Based on the findings of this review, several recommendations are proposed to improve the cost-effective prevention and management of DM and DR while reducing the growing global burden of visual impairment and healthcare expenditure.

6.1. Strengthening Preventive Healthcare Programs

Governments and healthcare institutions should prioritize preventive healthcare strategies rather than focusing predominantly on the treatment of advanced disease complications. Public health policies should emphasize early diagnosis of DM, routine DR screening, lifestyle modification programs, community health education and regular medical follow-up. Preventive interventions are significantly more cost-effective than managing advanced diabetic complications requiring hospitalization, surgery, and long-term rehabilitation.

6.2. Expansion of DR Screening Services

Comprehensive DR screening programs should be integrated into national healthcare systems, especially at the primary healthcare level. Routine retinal examinations should become mandatory components of diabetes management protocols.

Healthcare systems should increase availability of retinal imaging facilities, establish community-based screening programs, expand mobile eye clinics, improve referral systems, encourage annual eye examinations for all diabetic patients. Early detection through regular screening reduces blindness, lowers treatment costs, and improves quality of life.

6.3. Promotion of Teleophthalmology and Artificial Intelligence

Healthcare policymakers should invest in teleophthalmology and artificial intelligence-assisted retinal screening technologies, particularly in underserved and rural areas where access to ophthalmologists and retinal specialists is limited. Telemedicine and AI-based screening systems can increase screening coverage, reduce diagnostic delays, minimize transportation costs, reduce dependence on limited specialist manpower and improve healthcare efficiency.

These technologies are especially valuable in low- and middle-income countries facing shortages of eye care professionals and inadequate healthcare infrastructure.

6.4. Improvement of Patient Education and Public Awareness

Public awareness campaigns should be intensified to educate individuals about the risk factors for DM, the importance of glycaemic control, the benefits of regular exercise and healthy diet, the need for routine eye examinations and early symptoms of diabetic complications.

Health education should be incorporated into schools, workplaces, primary healthcare centers, and media platforms. Increased patient awareness improves treatment adherence, encourages early healthcare seeking behavior, and reduces disease progression.

6.5. Subsidization of Diabetes and Eye Care Services

Governments should provide subsidies for diabetic medications, retinal screening services, laboratory investigations, and ophthalmic treatments to reduce financial barriers to healthcare access.

Affordable healthcare financing mechanisms such as national health insurance schemes, public-private partnerships, community-based health insurance and subsidized drug programs should be strengthened to reduce out-of-pocket healthcare expenditure among diabetic patients.

Reducing treatment costs improves medication adherence and encourages routine follow-up care.

6.6. Strengthening Primary Healthcare Systems

Primary healthcare facilities should be equipped and empowered to manage diabetes and perform preliminary DR screening. Training healthcare workers at the primary care level can significantly improve early diagnosis and referral of patients.

Healthcare personnel including Optometrists, Ophthalmologists, Nurses, Pharmacists, Community health workers and General practitioners should receive continuous training in diabetic eye care and preventive management strategies.

Integrated multidisciplinary care models improve efficiency and reduce fragmentation of healthcare services.

6.7. Encouraging Research and Innovation

Further research should focus on low-cost retinal imaging technologies, AI-assisted screening systems, cost-benefit analyses of diabetic interventions, community-based preventive models, affordable pharmacological therapies and telemedicine implementation in low-resource settings.

Governments and research institutions should support innovation aimed at improving accessibility, affordability, and efficiency of diabetic care.

6.8. Enhancing Lifestyle Intervention Programs

Community-based lifestyle intervention programs should be strengthened to address modifiable risk factors such as Obesity, physical inutrition, poor nutrition, smoking and excessive alcohol consumption. Policies promoting healthy living through improved nutrition, urban planning for physical activity, and public fitness initiatives can significantly reduce diabetes incidence and long-term healthcare costs.

6.9. Improving Follow-Up Compliance

Healthcare systems should develop mechanisms to improve patient follow-up compliance through appointment reminder systems, mobile health applications, telemedicine follow-up services and community-based outreach programs.

Regular follow-up is essential for monitoring disease progression and preventing avoidable complications.

6.10. Global Collaboration and Policy Development

International organizations, governments, healthcare institutions, and non-governmental organizations should collaborate to develop sustainable policies for diabetes prevention and DR management.

Global partnerships may help improve healthcare funding, expand access to affordable technologies, promote knowledge sharing, strengthen healthcare infrastructure, and reduce disparities in diabetic eye care. A coordinated global approach is essential to effectively address the increasing burden of DM and DR.

Ultimately, investment in preventive healthcare, early screening, patient education, technological innovation, and integrated healthcare delivery remains the most sustainable and cost-effective strategy for reducing blindness, improving patient outcomes, and minimizing the economic burden associated with DM and DR.

7. CONCLUSION

DM and DR continue to constitute major global public health challenges with profound clinical, social, and economic consequences. The increasing prevalence of diabetes, driven by urbanization, sedentary lifestyles, obesity, population aging, and unhealthy dietary habits, has resulted in a corresponding rise in diabetic complications, particularly DR which remains one of the leading causes of preventable blindness among working-age adults worldwide. The chronic and progressive nature of these conditions imposes enormous financial pressure on patients, healthcare systems, caregivers, and governments, especially in low- and middle-income countries where healthcare resources are limited.

This review has demonstrated that the economic burden associated with DM and DR extends beyond direct medical expenses such as hospitalization, medications, laboratory investigations, retinal imaging, surgical procedures, and long-term follow-up care. Indirect costs including productivity loss, disability, unemployment, visual impairment, caregiver dependency, and reduced quality of life further compound the socioeconomic impact of these diseases. In many settings, delayed diagnosis and poor treatment adherence significantly worsen disease outcomes and increase healthcare expenditure.

Importantly, evidence from this review strongly indicates that preventive and early intervention strategies remain considerably more cost-effective than the management of advanced diabetic complications. Lifestyle modification, patient education, glycaemic control, blood pressure and lipid management, routine retinal screening, and early treatment substantially reduce disease progression, visual disability, and long-term healthcare costs. These preventive approaches not only improve clinical outcomes but also preserve productivity and enhance overall quality of life.

Advances in retinal imaging technologies, teleophthalmology, artificial intelligence-assisted screening systems, and portable diagnostic devices have further improved the accessibility and efficiency of DR screening and management. These innovations hold significant promise for reducing healthcare disparities, particularly in underserved and resource-constrained communities where access to specialized ophthalmic care remains inadequate. The integration of technology-driven healthcare solutions into primary healthcare systems may play a transformative role in reducing preventable blindness and improving healthcare delivery globally.

Furthermore, the review emphasizes the critical importance of multidisciplinary and integrated healthcare approaches involving ophthalmologists, optometrists, endocrinologists, nurses, pharmacists, nutritionists, primary healthcare providers, policymakers, and public health institutions. Collaborative healthcare delivery improves continuity of care, enhances patient compliance, and promotes efficient utilization of healthcare resources.

Despite substantial progress in diabetic care, several challenges persist, including poor public awareness, inadequate healthcare infrastructure, shortage of trained eye care professionals, high treatment costs, limited insurance coverage, and poor follow-up compliance. Addressing these barriers requires strong governmental commitment, increased healthcare investment, expansion of health insurance schemes, public-private partnerships, and sustained public health campaigns focused on diabetes prevention and early eye care intervention.

Ultimately, reducing the global burden of DM and DR requires a shift from reactive treatment models toward proactive, preventive, and cost-effective healthcare strategies. Investment in health education, early diagnosis, affordable screening technologies, integrated healthcare systems, and equitable access to treatment will not only reduce blindness and disability but also improve population health outcomes and strengthen healthcare sustainability. Through coordinated global efforts, technological innovation, and evidence-based healthcare policies, the devastating medical and economic consequences of DM and DR can be significantly minimized.

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