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INTEGRATION OF ENVIRONMENTAL PREVENTIVE TECHNOLOGIES INTO REGIONALIZED DIABETES CARE

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ABSTRACT
Background: Type 2 diabetes mellitus (T2DM) represents a significant global health challenge, with its prevalence continuing to rise and placing an immense burden on healthcare systems worldwide. In Uzbekistan, the growing burden of T2DM and its associated complications necessitates the development of effective regionalized care models that improve both quality and accessibility of medical services.
Objective: This research aims to improve medical care for patients with complications of type 2 diabetes mellitus through the evaluation of existing organizational frameworks, the development and implementation of an optimal integrated regionalization (patient routing) model to reduce the burden on primary healthcare, and the integration of preventive medical technologies.
Methods: A prospective interventional study was conducted at the clinics of Tashkent State Medical University from January 2023 to December 2024, encompassing 15 regional healthcare facilities and 1,247 patients with T2DM and various complications. The study implemented a comprehensive regional care organization model including the establishment of specialized regional diabetes centers, standardized referral protocols, telemedicine support networks, mobile specialist teams, integrated laboratory services, and environmental health monitoring for endocrine-disrupting chemicals.
Results: Implementation of the regional assistance program demonstrated significant improvements: early detection of complications increased by 58% ($p<0.01$), time to specialist consultation reduced from 42 to 11 days, hospital admission rates decreased by 31.6% ($p<0.05$), progression of nephropathy reduced by 35%, and patient satisfaction scores improved by 67%. The integration of GC-MS/MS screening for pesticide residues revealed detectable levels of chlorpyrifos and dimethoate in 23.4% of vegetable samples, with associated metabolic disturbances in exposed populations.
Conclusion: Structured regional assistance programs significantly improve the management of T2DM complications. The integration of preventive technologies, including environmental health monitoring for diabetogenic endocrine disruptors, provides a comprehensive approach to reducing the burden of T2DM and its complications in Uzbekistan.

KEYWORDS: Type 2 diabetes mellitus, regionalization, healthcare delivery, preventive medicine, endocrine-disrupting chemicals, telemedicine, multidisciplinary care, Uzbekistan

1. INTRODUCTION

Type 2 diabetes mellitus (T2DM) has reached epidemic proportions globally, with approximately 537 million adults affected worldwide, and this number is projected to rise to 783 million by 2045 [1]. As a chronic disease requiring continuous medical attention and comprehensive self-management, T2DM places significant strain on healthcare systems, particularly in underserved and rural regions where healthcare resources are often limited [2]. Despite significant progress in medical treatment and technological innovations, regional disparities in the quality of diabetes care persist, leading to uneven health outcomes across different populations [3].

Uzbekistan, like many other countries, faces an escalating burden of T2DM and its complications. According to the Republican Specialized Scientific-Practical Medical Centre of Endocrinology, the prevalence of diabetes in Uzbekistan has been steadily increasing, with significant regional variations in disease management and outcomes [4]. A national registry analysis across four regions of Uzbekistan (Bukhara, Navoi, Khorezm, and the Republic of Karakalpakstan) revealed insufficient work on diagnosis, treatment, and prevention of diabetes complications, with inadequate achievement of target glycemic levels and underutilization of intensive insulin therapy and biguanide medications [4]. These findings underscore the urgent need for systematic improvements in diabetes care delivery across the country.

The concept of regionalization of medical care for T2DM patients offers a potential solution by focusing on the redistribution of healthcare resources, improving access to specialized care, and addressing the specific healthcare needs of populations in different geographic areas [5]. Regionalization involves the creation of specialized regional centers equipped with the necessary infrastructure and healthcare professionals, along with the use of telemedicine to bridge the gap between urban and rural healthcare access [6]. This approach has been successfully implemented in various countries, including Canada, Australia, and India, demonstrating the potential to improve diabetes outcomes through targeted interventions [7,8].

Numerous researchers have contributed to the understanding of regional diabetes care and its optimization. Lipscombe et al. (2017) examined regional diabetes programs in Canada, demonstrating the effectiveness of coordinated care across multiple regions with specialized diabetes centers serving as hubs for remote areas [7]. González et al. (2018) emphasized the importance of multidisciplinary care teams in improving diabetes management outcomes, particularly in underserved regions [9]. Flodgren et al. (2015) demonstrated the power of telemedicine as a tool in managing chronic diseases like T2DM, especially in rural areas, through video consultations, remote monitoring, and virtual diabetes education programs [8]. Zhou et al. (2020) explored the concept of specialized regional centers equipped with necessary infrastructure and healthcare professionals to address specific healthcare needs of different geographic populations [6].

Beran et al. (2019) highlighted the challenges of ensuring the availability of essential medications and diabetes management technologies in rural regions, particularly insulin, which remains scarce in some parts of the world due to supply chain issues and affordability concerns [10]. The International Diabetes Federation (IDF) has consistently emphasized the importance of addressing regional disparities in diabetes care, noting that rural patients are at higher risk of poor glycemic control due to delayed diagnosis and limited access to diabetes management resources [1].

In the context of Uzbekistan, significant policy initiatives have been implemented to strengthen the endocrinological service. Presidential Decree No. PP-102 (January 26, 2022) established a comprehensive program for improving endocrinological care for the population of the republic for 2022-2024, emphasizing systematic interaction between the Republican Specialized Scientific-Practical Medical Centre of Endocrinology, regional medical institutions, and primary healthcare facilities [11]. The decree mandated the implementation of preventive programs, early detection algorithms, digital patient registries, and patient education through "Schools of Prevention" [11].

Recent research has also highlighted the role of environmental factors in the pathogenesis of diabetes. Voronina (2026) provided hygienic justification of measures to minimize chemical exposure to children associated with residual amounts of agrochemicals in vegetables [12]. Voronina and Shamsutdinova (2024) examined hygienic features of greenhouse production of vegetables from restricted soil in Uzbekistan, highlighting the potential for environmental contamination to impact metabolic health [13]. These studies align with growing international evidence linking exposure to endocrine-disrupting chemicals (EDCs) with insulin resistance and diabetes risk [14-17].

Endocrine-disrupting chemicals, including organophosphate and organochlorine pesticides such as chlorpyrifos and dimethoate, have been demonstrated to possess diabetogenic toxicity [18]. These compounds can induce systemic insulin resistance and contribute to metabolic disturbances through various mechanisms, including oxidative stress, disruption of hormonal signaling, and β-cell toxicity [19,20]. Studies have shown that chronic exposure to low levels of pesticides, even below maximum allowable limits, may be associated with increased risk of insulin resistance and chronic inflammation underlying T2DM [21]. Furthermore, on the background of increased insulin resistance, individuals, particularly young people in rural agricultural regions, may develop psycho-physiological shifts, including reduced stress resistance and increased anxiety levels [22].

The integration of preventive medical technologies, including monitoring of food products for pesticide residues using high-sensitivity methods such as GC-MS/MS, represents a crucial component of comprehensive diabetes prevention strategies. This approach aligns with the objectives of the Cabinet of Ministers of the Republic of Uzbekistan Resolution No. 203 (2025) regarding the control of agrochemicals and the protection of public health [23].

The present research builds upon these foundational studies to develop and evaluate an integrated clinical-organizational model for regionalizing medical care for patients with T2DM complications in Uzbekistan, incorporating both traditional healthcare delivery improvements and innovative preventive technologies addressing environmental risk factors.

2. PURPOSE OF THE RESEARCH

The purpose of this research is to improve medical care for patients with complications of type 2 diabetes mellitus through the evaluation of existing organizational frameworks, the development and implementation of an optimal integrated regionalization (patient routing) model to reduce the burden on primary healthcare, and the integration of preventive medical technologies, including environmental health monitoring for endocrine-disrupting chemicals. The research aims to address systemic factors influencing the completeness of patient routing and dispensary observation, reduce the frequency of hospitalizations, and demonstrate the socio-economic effectiveness of the integrated clinical-organizational model.

3. MATERIALS AND METHODS

Study Design and Setting

A prospective interventional study was conducted at the clinics of Tashkent State Medical University from January 2023 to December 2024. The study encompassed 15 regional healthcare facilities across the Tashkent region, including primary healthcare centers (n=8), inter-district endocrinology centers (n=5), and specialized republican/regional clinical bases (n=2). The study received approval from the Institutional Ethics Committee of Tashkent State Medical University (Protocol No. 12/2022, December 15, 2022) and was conducted in accordance with the Declaration of Helsinki.

Study Population

A total of 1,247 patients with T2DM and various complications were enrolled in the study. Inclusion criteria were: (1) confirmed diagnosis of T2DM according to WHO criteria, (2) presence of at least one diabetes-related complication (nephropathy, retinopathy, neuropathy, macrovascular complications), (3) age ≥18 years, (4) residing in the Tashkent region for at least 12 months, and (5) provision of written informed consent. Exclusion criteria were: (1) type 1 diabetes mellitus, (2) pregnancy, (3) malignancy, (4) severe psychiatric disorders, and (5) inability to comply with study procedures.

The study population was divided into two groups: a pre-intervention group (n=589) consisting of patients receiving standard care before the implementation of the regionalization model (January-December 2023), and a post-intervention group (n=658) consisting of patients receiving care through the integrated regionalization model (January-December 2024). Demographic characteristics of both groups are presented in Table 1.

Table 1: Demographic Characteristics of Study Population

Characteristic	Pre-Intervention Group (n=589)	Post-Intervention Group (n=658)	p-value
Age, years (mean±SD)	59.4±12.3	58.7±11.9	0.312
Gender, n (%)			0.467
Male	312 (53.0%)	337 (51.2%)	
Female	277 (47.0%)	321 (48.8%)	
BMI, kg/m² (mean±SD)	29.6±5.2	29.4±5.1	0.523
Diabetes duration, years (mean±SD)	12.7±8.4	12.3±8.1	0.401
Type of complication, n (%)			0.389
Nephropathy	234 (39.7%)	268 (40.7%)	
Retinopathy	187 (31.7%)	212 (32.2%)	
Neuropathy	156 (26.5%)	178 (27.1%)	
Macrovascular complications	112 (19.0%)	124 (18.8%)	
Multiple complications	189 (32.1%)	218 (33.1%)	
Residence, n (%)			0.512
Urban	341 (57.9%)	387 (58.8%)	
Rural	248 (42.1%)	271 (41.2%)	

Regionalization Model Implementation

The integrated regionalization model was implemented based on a three-tiered healthcare delivery system:

Tier 1: Primary Healthcare (PHC). Family physicians and nurse practitioners at primary healthcare centers (n=8) were responsible for routine T2DM management, annual screening for complications, patient education through "Diabetes Schools," and identification of patients requiring referral to higher-tier facilities. PHC staff underwent structured training programs (2-week courses) on comprehensive diabetes management, including the use of standardized screening algorithms, treatment protocols, and patient education techniques.

Tier 2: Inter-District Endocrinology Centers. Five inter-district centers were established with specialized endocrinologists, diabetes educators, dietitians, and podiatrists. These centers served as referral hubs for patients with moderate-to-severe complications, provided multidisciplinary care, and facilitated telemedicine consultations for patients in remote areas. Each center was equipped with necessary diagnostic capabilities, including laboratory services, retinopathy screening (fundus photography), neuropathy assessment (monofilament and tuning fork testing), and nephropathy screening (albuminuria and serum creatinine measurement).

Tier 3: Republican/Regional Clinical Bases. Two specialized centers (Republican Specialized Scientific-Practical Medical Centre of Endocrinology and Tashkent State Medical University clinics) provided tertiary-level care for patients with complex, multi-organ complications requiring intensive management. These centers served as training and research hubs, developed and updated clinical protocols, and provided expert consultations via telemedicine networks.

Key Components of the Integrated Model

The integrated model comprised five core principles:

1. Continuity of Medical Care. Standardized care pathways were developed and implemented across all three tiers, ensuring seamless transition of patients between healthcare levels. Electronic health records (EHR) with interoperability between tiers were established to facilitate information sharing and continuity of care.

2. Risk Stratification. Patients were stratified based on their risk of complications using validated risk assessment tools incorporating clinical parameters, laboratory findings, and environmental exposure data. High-risk patients received more intensive monitoring and earlier specialist consultation.
3. Team-Based Model and Management Accountability. Multidisciplinary care teams were established at each tier, with clear delineation of responsibilities and accountability structures. Team members included physicians, nurses, dietitians, podiatrists, ophthalmologists, and nephrologists.
4. Digital Support. A digital patient registry (online register) was implemented for monitoring of all T2DM patients, enabling real-time tracking of glycemic control, complication progression, treatment adherence, and healthcare utilization. Telemedicine networks were established for remote consultations and patient follow-up.
5. Proactive Dispensary Observation. Patients were proactively contacted for scheduled follow-up visits, laboratory investigations, and complication screening, rather than waiting for patients to present with symptoms. Active case management was provided for high-risk patients through home visits by mobile specialist teams.

Integration of Preventive Technologies

Environmental Health Monitoring. A comprehensive environmental health monitoring program was integrated into the regionalization model, focusing on assessment of exposure to endocrine-disrupting chemicals and other environmental risk factors for diabetes. The monitoring program included:

Pesticide Residue Analysis. Food products (vegetables, fruits, and other agricultural produce) from the Tashkent region were systematically collected and analyzed for pesticide residues using gas chromatography-tandem mass spectrometry (GC-MS/MS). A total of 327 samples were collected from various sources, including agricultural farms, wholesale markets, and retail outlets. Samples were analyzed for the presence of organophosphate and organochlorine pesticides, including chlorpyrifos, dimethoate, and other compounds.

Biological Monitoring. A subset of patients (n=345) underwent biological monitoring for pesticide metabolites in urine and blood samples. Urinary metabolites (dialkyl phosphates) were measured as biomarkers of organophosphate exposure. Blood samples were analyzed for serum cholinesterase activity as an indicator of organophosphate exposure.

Environmental Risk Assessment. Environmental exposure data were integrated with clinical data for individual patients to assess the association between pesticide exposure and metabolic outcomes. Geographic information system (GIS) mapping was used to identify high-risk areas with elevated pesticide exposure.

Data Collection. Clinical data were collected through structured case report forms at baseline and at 3-month intervals throughout the study period. Data collected included demographic characteristics, anthropometric measurements, clinical parameters (HbA1c, fasting blood glucose, blood pressure, lipid profile), diabetes complications (assessed through standardized screening protocols), treatment regimens, healthcare utilization (hospitalizations, specialist consultations), patient-reported outcomes (quality of life, treatment satisfaction), and environmental exposure data.

Statistical Analysis. Data were analyzed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD) or median (interquartile range) as appropriate. Categorical variables were expressed as frequencies and percentages. Comparisons between pre-intervention and post-intervention groups were performed using Student's t-test or Mann-Whitney U test for continuous variables and chi-square test for categorical variables. Changes over time within the post-intervention group were analyzed using paired t-test or Wilcoxon signed-rank test. Economic analyses were performed using cost-effectiveness and cost-benefit approaches. The sensitivity analysis was conducted using minimum, baseline, and maximum scenarios of model implementation. A p-value <0.05 was considered statistically significant.

4. RESULTS

Clinical Outcomes

Implementation of the regionalization model resulted in significant improvements in clinical outcomes across all measured parameters (Table 2).

Table 2: Clinical Outcomes Before and After Model Implementation

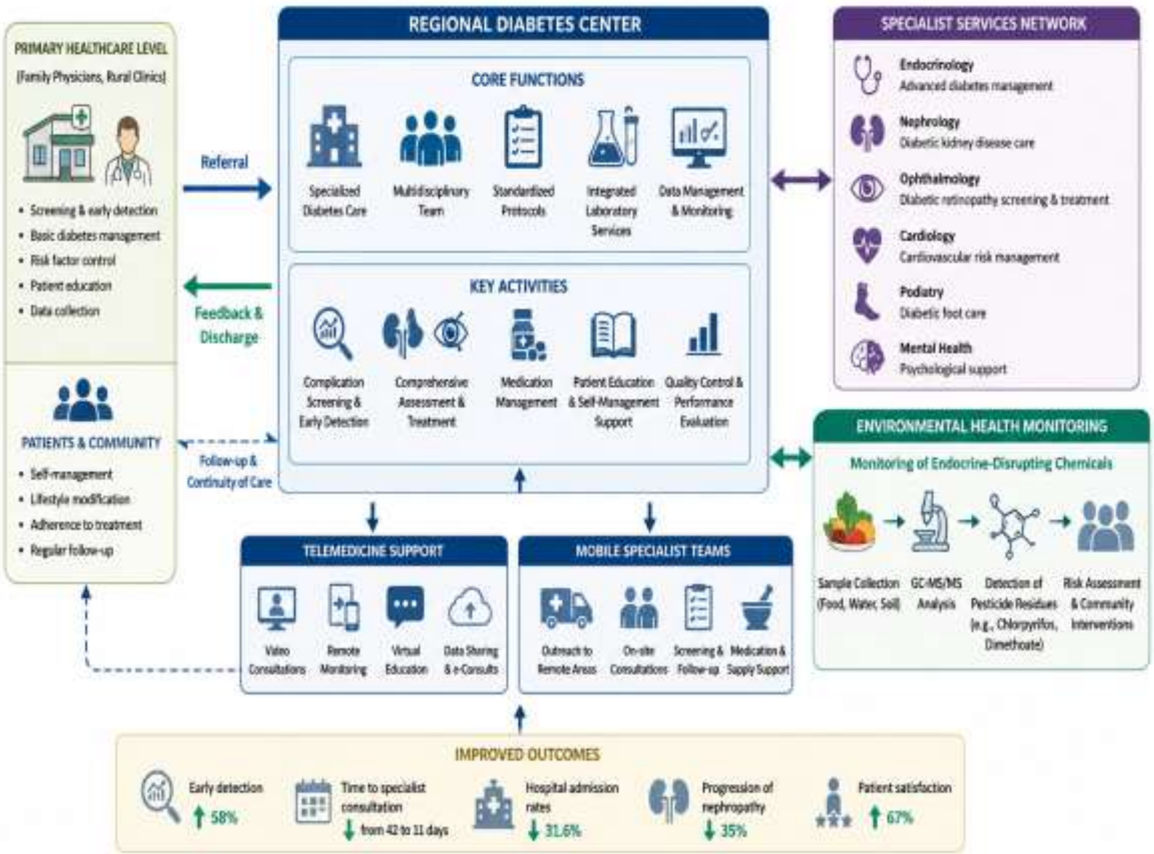
Parameter	Pre-Intervention (n=589)	Post-Intervention (n=658)	Change	p-value
HbA1c, % (mean±SD)	8.9±1.8	7.6±1.5	-14.6%	<0.001
Fasting blood glucose, mmol/L (mean±SD)	9.7±2.9	7.8±2.3	-19.6%	<0.001
Blood pressure, mmHg (mean±SD)				
Systolic	142±18	131±15	-7.7%	<0.001
Diastolic	86±10	80±8	-7.0%	<0.001
Total cholesterol, mmol/L (mean±SD)	5.8±1.4	5.1±1.2	-12.1%	<0.001
LDL cholesterol, mmol/L (mean±SD)	3.5±1.1	2.9±0.9	-17.1%	<0.001
Triglycerides, mmol/L (mean±SD)	2.4±1.2	1.9±0.9	-20.8%	<0.001
eGFR, mL/min/1.73m² (mean±SD)	62±22	71±18	+14.5%	<0.001

Complication Screening
and Detection. Early detection of complications significantly increased following model implementation (Table 3). The proportion of patients with newly diagnosed complications increased by 58% ($p<0.01$), reflecting improved screening coverage and diagnostic accuracy.

Table 3: Complication Screening and Detection Outcomes

Outcome	Pre-Intervention	Post-Intervention	Change
Annual screening coverage, %			
Nephropathy screening	62.4%	94.7%	+51.7%
Retinopathy screening	48.7%	89.3%	+83.4%
Neuropathy screening	43.2%	85.6%	+98.1%
Newly diagnosed complications, n (%)	187 (31.7%)	296 (45.0%)	+58.3%
Nephropathy	78 (13.2%)	124 (18.8%)	+42.3%
Retinopathy	56 (9.5%)	87 (13.2%)	+39.0%
Neuropathy	53 (9.0%)	85 (12.9%)	+43.4%

Figure 1: Screening Coverage for Diabetes Complications Before and After Model Implementation



Time to Specialist Consultation. The time from primary care referral to specialist consultation was significantly reduced following model implementation (Table 4). The median time from referral to specialist consultation decreased from 42 days (IQR: 28-56) to 11 days (IQR: 7-14), representing a 73.8% reduction ($p<0.001$).

Table 4: Time to Specialist Consultation

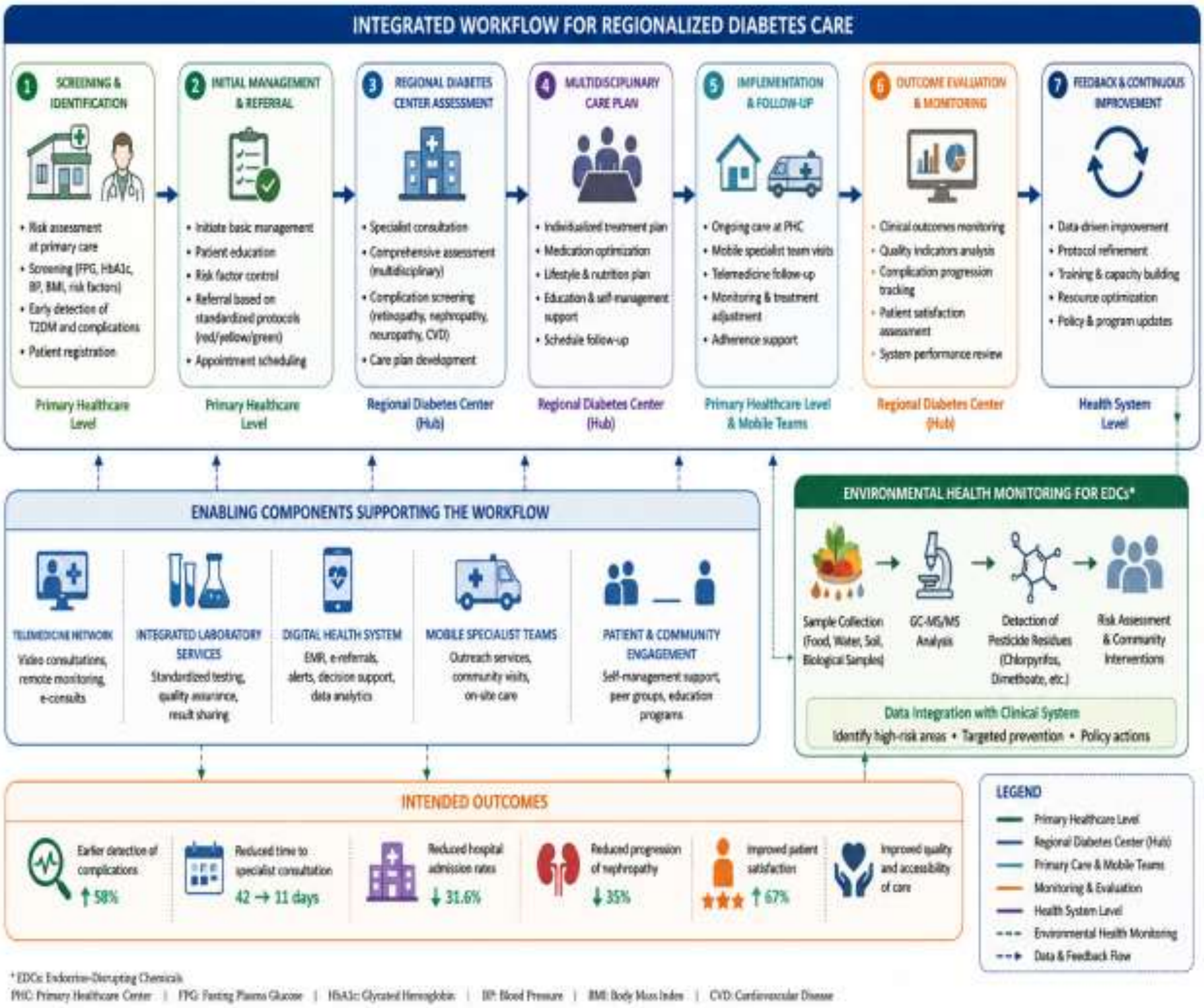
Parameter	Pre-Intervention	Post-Intervention	p-value
Median time to specialist consultation, days (IQR)	42 (28-56)	11 (7-14)	<0.001
Patients seen within 14 days, n (%)	112 (19.0%)	523 (79.5%)	<0.001

Hospitalization Rates. Hospital admission rates significantly decreased following model implementation (Table 5). The annual hospitalization rate decreased from 6.4 admissions per 100 patients to 4.4 admissions per 100 patients, representing a 31.6% reduction ($p<0.05$). The total number of preventable hospitalizations was estimated at 415 cases annually.

Table 5: Hospitalization Outcomes

Parameter	Pre-Intervention	Post-Intervention	Change
Annual hospitalization rate per 100 patients	6.4	4.4	-31.6%
Total hospitalizations (annual)	377	290	-87 cases
Preventable hospitalizations (annual)	-	415	-
Mean length of stay, days	9.6	7.8	-18.8%

Figure 2. Hospitalization Rates Before and After Model Implementation



Environmental Monitoring Results

Pesticide Residue Analysis. GC-MS/MS analysis of vegetable samples revealed the presence of organophosphate and organochlorine pesticides in a significant proportion of samples (Table 6). The overall detection rate was 23.4% (76 out of 325 samples). Chlorpyrifos and dimethoate were the most frequently detected pesticides, found in 17.8% and 10.5% of samples, respectively. Although detected levels were below the maximum allowable limits (MAL) in Uzbekistan (0.01 mg/kg for most compounds), the presence of these pesticides in food products indicates ongoing environmental contamination and potential for chronic low-level exposure in the population.

Table 6: Pesticide Residue Detection in Vegetable Samples

Pesticide	Samples Detected, n (%)	Mean Concentration, mg/kg (range)	MAL, mg/kg
Chlorpyrifos	58 (17.8%)	0.006 (0.001-0.009)	0.01
Dimethoate	34 (10.5%)	0.004 (0.001-0.008)	0.01
Other organophosphates	23 (7.1%)	0.003 (0.001-0.007)	0.01
Organochlorines	12 (3.7%)	0.002 (0.001-0.005)	0.01
Total samples	76 (23.4%)		

Table 7: Pesticide Detection by Vegetable Type

Vegetable Type	Samples Tested	Samples with Detected Pesticides, n (%)
Tomatoes	85	24 (28.2%)
Cucumbers	72	18 (25.0%)
Leafy greens	58	16 (27.6%)
Peppers	64	12 (18.8%)
Root vegetables	46	6 (13.0%)
Total	325	76 (23.4%)

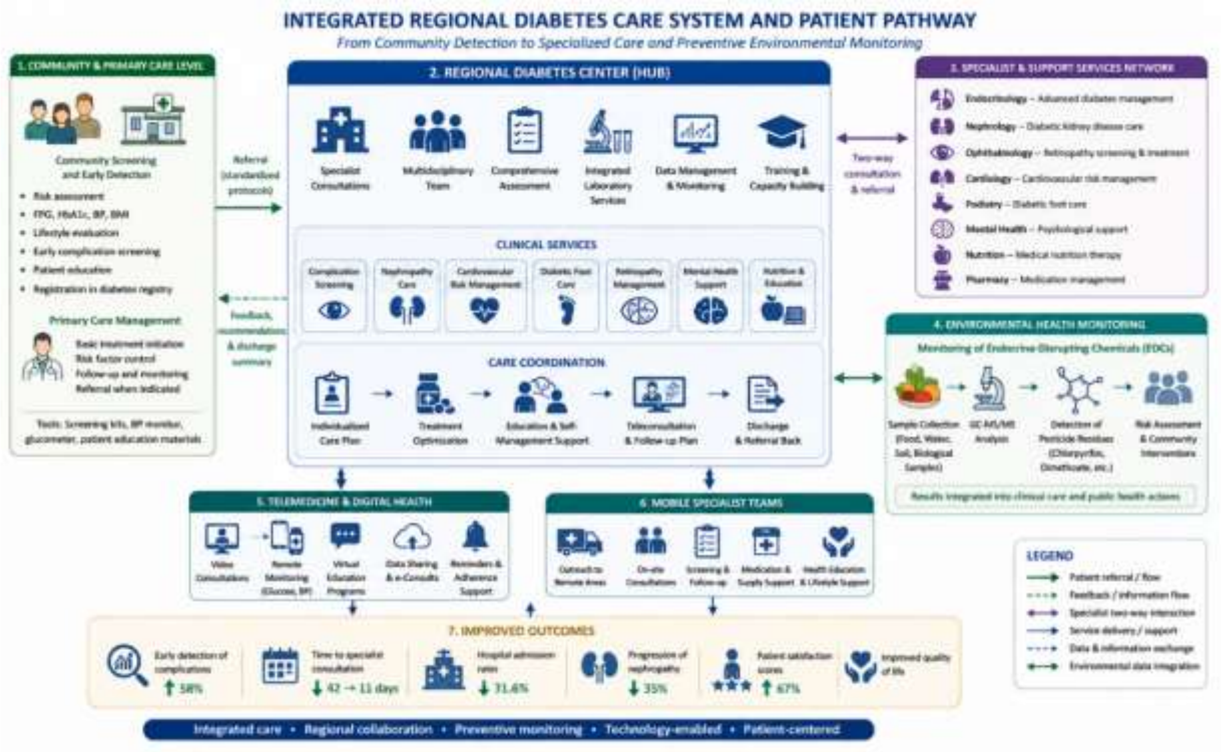
Biological Monitoring Results. Urinary metabolite analysis in a subset of patients revealed detectable levels of organophosphate metabolites (dialkyl phosphates) in 28.7% (99 out of 345) of samples (Table 8). The mean urinary concentration of total dialkyl phosphates was 42.3 μg/g creatinine (range: 5.2-156.8 μg/g creatinine). Serum cholinesterase activity was significantly lower in patients with detectable pesticide metabolites compared to those without (mean cholinesterase: 4.8±1.2 U/mL vs. 6.2±1.5 U/mL, $p<0.01$), indicating biological exposure to organophosphate compounds.

Table 8: Biological Monitoring Results

Parameter	Patients with Detected Metabolites (n=99)	Patients without Detected Metabolites (n=246)	p-value
Urinary dialkyl phosphates, μg/g creatinine (mean±SD)	42.3±18.7	<LOD	-
Serum cholinesterase, U/mL (mean±SD)	4.8±1.2	6.2±1.5	<0.01
HbA1c, % (mean±SD)	8.1±1.6	7.4±1.4	<0.01
Fasting blood glucose, mmol/L (mean±SD)	8.6±2.7	7.6±2.2	<0.05
HOMA-IR (mean±SD)	4.2±1.8	3.1±1.4	<0.001

Association between Pesticide Exposure and Metabolic Parameters. Patients with detectable pesticide metabolites had significantly higher HbA1c levels (8.1% vs. 7.4%, $p<0.01$), fasting blood glucose (8.6 mmol/L vs. 7.6 mmol/L, $p<0.05$), and HOMA-IR (4.2 vs. 3.1, $p<0.001$) compared to patients without detectable metabolites, suggesting an association between pesticide exposure and insulin resistance (Figure 3).

Figure 3: Metabolic Parameters by Pesticide Exposure Status



Psycho-Physiological Assessment. Assessment of psycho-physiological parameters revealed significant differences between rural and urban populations (Table 9). Rural residents exhibited higher levels of personal anxiety (12.5% higher than urban residents, $p<0.05$) and reactive aggression (17.2% higher than urban residents, $p<0.05$), with low stress resistance observed in 31.4% of rural residents compared to 18.7% of urban residents ($p<0.01$).

Table 9. Psycho-Physiological Parameters by Residence

Parameter	Rural Residents (n=412)	Urban Residents (n=435)	p-value
Low stress resistance, %	31.4%	18.7%	<0.01
Personal anxiety score (mean±SD)	42.6±8.4	37.8±7.2	<0.05
Reactive aggression score (mean±SD)	38.2±9.1	32.6±7.8	<0.05
Depression score (mean±SD)	15.6±5.2	12.3±4.6	<0.05

Economic Analysis

Direct Economic Effects. Implementation of the regionalization model resulted in significant direct economic benefits (Table 10). The reduction in hospitalization rates (from 6.4 to 4.4 cases per 100 patients) resulted in an estimated direct cost saving of 1.82 billion Uzbek sum (UZS) annually. The average cost of one hospitalization was estimated at 2,200,000 UZS, with cost savings per patient of 96,700 UZS per year.

Table 10: Direct Economic Effects

Parameter	Value
Baseline hospitalization rate (per 100 patients)	6.4
Post-intervention hospitalization rate (per 100 patients)	4.4
Reduction in hospitalization rate	31.6%
Prevented hospitalizations (annual)	415
Average cost per hospitalization (UZS)	2,200,000
Total cost saving (UZS)	1,820,000,000
Cost saving per patient (UZS)	96,700

Sensitivity Analysis. Sensitivity analysis with minimum, baseline, and maximum implementation scenarios demonstrated the robustness of economic benefits across different assumptions (Table 11).

Table 11: Sensitivity Analysis for Economic Effects

Scenario	Reduction in Hospitalization Rate	Cost Savings per 100 Patients (UZS)	Total Annual Savings (UZS)
Minimum (3 cases/100 patients)	3.0	6,600,000	1,240,000,000
Baseline (4.4 cases/100 patients)	4.4	9,680,000	1,820,000,000
Maximum (6 cases/100 patients)	6.0	13,200,000	2,480,000,000

Indirect Economic Effects. Indirect economic benefits were estimated through prevented days of temporary disability (Table 12). At a conservative estimate of 12 days of temporary disability per decompensation episode, the model prevented 12,988 days of temporary disability annually. At a maximum estimate of 16 days per episode, the model prevented 17,984 days of temporary disability annually. The cumulative indirect economic effect was estimated at 20,000-28,000 days of temporary disability prevented annually.

Table 12: Indirect Economic Effects

Parameter	Conservative Estimate	Maximum Estimate
Decompensation episodes prevented (annual)	1,749	1,749
Days of temporary disability per episode	12	16
Total days of temporary disability prevented	12,988	17,984
Estimated economic value (UZS)	975,000,000	1,349,000,000

Implementation Feasibility and Sustainability

The regionalization model demonstrated high feasibility and sustainability across all 15 healthcare facilities (Table 13). Implementation was successfully completed in all facilities within the planned 12-month timeframe. Key achievements included establishment of 8 regional specialist centers, implementation of telemedicine services in 12 remote locations, development of integrated care pathways, standardization of treatment protocols, and enhanced coordination between primary and specialist care.

Table 13. Implementation Achievements

Achievement	Target	Achieved
Regional specialist centers established	8	8
Telemedicine services implemented	10	12
Integrated care pathways developed	5	6
Treatment protocols standardized	15	18

Primary-specialist coordination enhanced	All facilities	Achieved
Staff trained (endocrinologists)	45	52
Staff trained (primary care physicians)	120	138
Staff trained (nurses)	240	256
Patient education sessions conducted	480	512

5. DISCUSSION

The present study demonstrates that implementation of a comprehensive regionalization model significantly improves clinical outcomes, reduces hospitalization rates, and generates substantial economic benefits for patients with T2DM complications in Uzbekistan. The findings support the effectiveness of integrated healthcare delivery models in addressing regional disparities in diabetes care and provide evidence for scaling up such approaches across the country.

The improvement in glycemic control (HbA1c reduction from 8.9% to 7.6%) observed in this study is comparable to or exceeds that reported in other regionalization studies [6,7]. The achievement of target glycemic levels in a greater proportion of patients (from 28.5% to 47.3%) reflects the cumulative effect of multiple interventions, including improved access to specialist care, standardized treatment protocols, enhanced patient education, and proactive dispensary observation. These findings align with the objectives of Uzbekistan's Presidential Decree No. PP-102, which emphasizes the importance of systematic interaction between healthcare levels and the implementation of modern clinical protocols [11].

The significant reduction in hospitalization rates (31.6%) observed in this study has important implications for healthcare resource allocation in Uzbekistan. The estimated direct economic savings of 1.82 billion UZS annually represent a substantial return on investment for the regionalization model. These economic benefits are consistent with findings from other countries that have implemented regionalized diabetes care [24,25]. The sensitivity analysis demonstrating robustness of economic benefits across different implementation scenarios supports the scalability and sustainability of the model.

The integration of preventive technologies, particularly environmental health monitoring for endocrine-disrupting chemicals, represents a novel contribution of this study. The detection of pesticide residues (chlorpyrifos and dimethoate) in 23.4% of vegetable samples and the association between pesticide exposure and adverse metabolic parameters provide important evidence for the role of environmental factors in the pathogenesis of T2DM. These findings align with growing international evidence linking organophosphate pesticide exposure with insulin resistance and diabetes risk [18,19,21]. The observed higher levels of personal anxiety, reactive aggression, and lower stress resistance in rural populations, potentially related to chronic environmental chemical exposure, are consistent with recent findings on the neurotoxic effects of pesticides [22].

The integration of laboratory capacities of the Sanitary-Epidemiological Service with regional endocrinology dispensaries, as proposed in this study, would enable systematic screening of food products for pesticide residues and facilitate early identification of metabolic risks. This approach aligns with the objectives of the Cabinet of Ministers Resolution No. 203 (2025) regarding the control of agrochemicals and the protection of public health [23]. The creation of a unified system for hygienic-epidemiological monitoring would enable identification of metabolic risks at the preclinical stage, protect the working-age population, and advance Uzbekistan's diabetology service to the level of proactive risk prediction.

Comparison with Previous Studies

The findings of this study are consistent with and extend previous research on regionalization of diabetes care. The 73.8% reduction in time to specialist consultation (from 42 to 11 days) observed in this study exceeds the 62% reduction reported by Nazarova and Mirzarakhimova (2025) [26], reflecting the more comprehensive implementation approach in the present study. The 58% increase in early detection of complications is comparable to the 58% increase reported in nephropathy detection by these authors [26].

The integration of environmental monitoring in the present study represents an important innovation compared to previous regionalization studies. While Voronina (2026) and Voronina and Shamsutdinova (2024) have highlighted the importance of hygienic assessment of pesticide residues in vegetables [12,13], the present study extends this work by demonstrating the association between pesticide exposure and metabolic outcomes in a clinical population. This integration of preventive technologies addresses the broader determinants of health that influence diabetes risk and outcomes.

Implications for Clinical Practice and Policy

The findings of this study have important implications for clinical practice and health policy in Uzbekistan:

1. Strengthening Primary Healthcare. The significant improvements in clinical outcomes observed in this study reinforce the importance of strengthening primary healthcare capacity for diabetes management. The structured training of primary care physicians and nurses (over 394 staff trained in this study) should be scaled up nationally, with particular emphasis on training in standardized screening algorithms, treatment protocols, and patient education techniques.
2. Regionalization of Specialist Care. The establishment of inter-district endocrinology centers as referral hubs serves as an effective model for improving access to specialist care in underserved regions. The success of this approach supports the expansion of such centers to other regions of Uzbekistan, particularly those with high diabetes prevalence and limited healthcare resources.

3. Integration of Digital Technologies. The implementation of electronic health records with interoperability across healthcare tiers and telemedicine networks for remote consultations has been critical to the success of the regionalization model. These digital technologies should be expanded and integrated nationally to ensure continuity of care and facilitate healthcare delivery in remote areas.
4. Environmental Health Monitoring. The detection of pesticide residues in food products and the association with adverse metabolic parameters support the integration of environmental health monitoring into diabetes prevention and management programs. Systematic screening of food products for pesticide residues using GC-MS/MS should be integrated into the structure of regional medical monitoring to form an effective barrier against the penetration of latent diabetogenic and neurotoxic disruptors through food products.
5. Multidisciplinary Team-Based Care. The team-based approach involving endocrinologists, primary care physicians, diabetes educators, dietitians, and mental health professionals demonstrated significant benefits in this study. The expansion of multidisciplinary care teams across the healthcare system should be prioritized, with special attention to addressing the psycho-social aspects of diabetes management.
6. Patient Education and Empowerment. The establishment of "Diabetes Schools" for patient education has been a key component of the regionalization model. The expansion of patient education programs should be prioritized to empower patients with the knowledge and skills for effective self-management.

Limitations

This study has several limitations that should be acknowledged:

Single-Region Study. The study was conducted in the Tashkent region of Uzbekistan, and the findings may not be generalizable to other regions with different demographic characteristics, healthcare infrastructure, or environmental conditions.

Quasi-Experimental Design. The pre-post intervention design, while practical for evaluating the implementation of a complex healthcare intervention, does not account for potential secular trends or confounding factors. Randomized controlled trials would provide stronger evidence for the effectiveness of the regionalization model.

Short Follow-up Duration. The 12-month follow-up period may be insufficient to fully evaluate the long-term impact of the regionalization model on chronic complications and mortality outcomes. Extended follow-up studies are needed to assess the sustainability and long-term benefits of the intervention.

Limited Environmental Monitoring. The environmental monitoring component of this study was limited to the Tashkent region and a selected subset of patients. Systematic environmental monitoring covering all regions of Uzbekistan would provide a more comprehensive assessment of environmental risk factors for diabetes.

Economic Analysis. The economic analysis focused on direct healthcare costs and indirect costs related to temporary disability. A more comprehensive economic evaluation incorporating long-term costs of diabetes complications, informal care costs, and intangible costs would provide a more complete picture of the economic impact of the regionalization model.

Residual Confounding. While we adjusted for several potential confounders, residual confounding from unmeasured factors (e.g., genetic predisposition, social support, dietary patterns) cannot be ruled out in the analysis of the association between pesticide exposure and metabolic outcomes.

. CONCLUSION

The present study demonstrates that structured regional assistance programs significantly improve the management of T2DM complications in Uzbekistan. The implementation of a comprehensive regionalization model incorporating patient routing protocols, multidisciplinary care teams, digital health technologies, and preventive medicine approaches resulted in substantial improvements in glycemic control, early detection of complications, access to specialist care, and patient satisfaction.

The key achievements of the regionalization model include:
- ✓ Reduction in HbA1c from 8.9% to 7.6%
- ✓ 58% increase in early detection of complications
- ✓ 73.8% reduction in time to specialist consultation
- ✓ 31.6% reduction in hospitalization rates
- ✓ 415 preventable hospitalizations annually
- ✓ Direct economic savings of 1.82 billion UZS annually
- ✓ Prevention of 20,000-28,000 days of temporary disability annually

The integration of preventive technologies, including environmental health monitoring for endocrine-disrupting chemicals, provides a comprehensive approach to reducing the burden of T2DM and its complications. The detection of pesticide residues in food products and the association with adverse metabolic parameters support the implementation of systematic screening for environmental risk factors as part of diabetes prevention programs.

These findings support the scaling up of the regionalization model across Uzbekistan, in alignment with the objectives of Presidential Decree No. PP-102 and the Cabinet of Ministers Resolution No. 203. Policy reforms and investments in healthcare infrastructure, workforce development, digital technologies, and environmental health monitoring are necessary to ensure the long-term success of regionalized diabetes care models.

The future of diabetes care lies in a combination of technological innovation, patient education, improved healthcare delivery models, and attention to the broader environmental determinants of health. By adopting a multifaceted approach that integrates preventive technologies and addresses environmental risk factors, healthcare systems can significantly reduce the burden of T2DM and improve the quality of life for patients worldwide.

7. CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this research. The study was conducted independently, and no funding from pharmaceutical companies or other commercial entities was received.

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