Digital ecosystems for cancer prevention: integrating citizen engagement, clinical decision support, and policy analytics

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Abstract
As smart cities increasingly rely on interconnected digital infrastructures, healthcare systems must adopt secure, intelligent, and data-driven approaches capable of supporting large-scale prevention strategies and resilient public health services. Colorectal cancer (CRC) remains a major public health challenge in Europe, requiring integrated solutions that combine citizen engagement, clinical intelligence, and policy-oriented analytics. Traditional prevention approaches are often affected by fragmented data flows, limited personalization, and insufficient interoperability between healthcare stakeholders. This paper explores the role of the ONCODIR digital ecosystem in supporting intelligent and prevention-oriented healthcare infrastructures through three core components: NELI, DEPO, and DELI. NELI, a citizen-oriented mobile application, enables individuals to monitor lifestyle factors, receive personalized recommendations, and actively participate in prevention practices. DEPO provides AI-based clinical decision support capabilities that enhance medical workflows through data-driven recommendations and personalized counselling. DELI, the policy analytics dashboard, supports evidence-based governance by enabling the analysis of aggregated health indicators and intervention outcomes for public health planning. The research adopts an implementation-oriented analytical approach focused on how integrated digital platforms contribute to resilient healthcare ecosystems and multi-level decision-making within smart city environments. The study investigates how interoperable digital tools transform behavioural and clinical data into actionable intelligence while supporting stakeholder engagement, prevention efficiency, and policy coordination. The findings highlight the potential of intelligent digital health ecosystems to strengthen preventive healthcare services, improve data-driven governance, and support the development of cyber-resilient and citizen-centred smart healthcare infrastructures. By integrating AI-enabled decision support, participatory engagement, and policy analytics, the proposed framework contributes to the advancement of secure and sustainable digital public health systems within future smart cities.

Keywords: Digital public health, Smart healthcare infrastructures, FAIR data, Interoperability

1. Introduction

1.1 Colorectal Cancer Prevention in Digital Healthcare Ecosystems

Colorectal cancer (CRC) remains one of the most significant public health challenges in Europe and worldwide. Global estimates indicate that CRC is among the most frequently diagnosed cancers, with more than 1.9 million new cases and over 900,000 deaths reported in 2022 [1]. At the European level, CRC is also a major contributor to cancer incidence, mortality, and healthcare expenditure, requiring sustained prevention, early detection, and risk-reduction strategies [2]. Although screening programmes and lifestyle-oriented interventions can reduce the burden of CRC, their effectiveness depends on citizens'

awareness, accessibility of services, continuity of care, and the ability of healthcare systems to translate heterogeneous data into actionable prevention measures.

The increasing digitalisation of healthcare creates new opportunities to strengthen prevention-oriented public health systems. In the broader context of smart cities, healthcare services are becoming part of interconnected digital ecosystems in which mobile applications, Internet of Things (IoT) devices, data repositories, artificial intelligence (AI), and policy dashboards can support real-time monitoring and decision-making [3]. Smart healthcare infrastructures are not limited to clinical institutions; they increasingly extend toward citizens, local communities, and public authorities. This shift is particularly relevant for prevention, where behavioural risk factors such as diet, physical activity, alcohol consumption, smoking, and health literacy are strongly linked to long-term outcomes.

Digital ecosystems for cancer prevention can therefore be understood as integrated socio-technical environments that connect citizens, clinicians, and policymakers around a shared evidence base. In such ecosystems, citizen-facing tools support engagement and self-monitoring, clinical decision support tools assist healthcare professionals in interpreting patient information, and policy analytics dashboards enable aggregated analysis for governance and planning. This direction is consistent with recent research on smart hospital governance, which highlights the importance of interoperability, infrastructure, workforce capacity, cybersecurity, and governance frameworks for successful digital transformation in healthcare [4].

The ONCODIR project follows this ecosystem logic by developing a set of complementary tools for CRC prevention: NELI, a citizen-oriented mobile application; DEPO, an AI-based clinical counselling and decision-support dashboard; and DELI, a policy analytics dashboard. Rather than treating prevention as a single clinical interaction, the project positions it as a multi-level process involving behavioural monitoring, personalized guidance, clinical oversight, and policy-oriented intelligence.

1.2 Challenges in Prevention-Oriented Healthcare Systems

Despite the potential of digital health technologies, prevention-oriented healthcare systems face several persistent challenges. First, health data are often fragmented across institutions, platforms, registries, and administrative systems. This fragmentation limits interoperability and makes it difficult to create a continuous view of risk factors, individual behaviours, and population-level trends. In cancer prevention, this challenge is particularly relevant because effective interventions require the combination of clinical, behavioural, demographic, socio-economic, and policy data.

Second, prevention strategies often struggle to achieve sustained citizen engagement. Digital tools can support personalised feedback and self-monitoring, but their impact depends on usability, trust, digital inclusion, and health literacy. Studies on smart cities and digital inclusion show that digital transformation does not automatically reduce inequalities; older citizens, digitally vulnerable groups, and communities with lower access to digital services may require specific support mechanisms [5]. This is especially important in CRC prevention, where lack of awareness, complex registration processes,

limited access to services, and insufficiently tailored communication can reduce participation in preventive programmes.

Third, clinical workflows are under pressure. Healthcare professionals often face high workloads and limited time for personalised counselling, especially in primary care and prevention settings. AI-based clinical decision support systems can help by summarising relevant data and generating recommendations, but their adoption depends on transparency, explainability, usability, trust, and alignment with clinical responsibility [6]. Therefore, such systems should support, rather than replace, professional judgement.

Fourth, policy decisions in cancer prevention require reliable aggregated evidence. Policymakers need to compare risk factors, identify vulnerable groups, evaluate interventions, and allocate resources efficiently. However, public health planning is frequently constrained by differences in national strategies, limited standardisation, and insufficient integration between evidence generation and policy implementation. The European context also shows the need for harmonised standards, ethical data sharing, and cross-country collaboration in prevention programmes.

Finally, digital healthcare ecosystems must address cybersecurity, privacy, and ethical governance. Health data are highly sensitive, and smart healthcare infrastructures increase the number of actors, devices, and data flows involved in service delivery. Algorithmic systems used in public health may also raise concerns regarding transparency, proportionality, misuse, and the balance between collective benefit and individual rights [7]. For this reason, prevention-oriented digital ecosystems must be designed according to principles of data minimisation, GDPR compliance, role-based access, auditability, and secure interoperability.

Another challenge concerns the operational adoption of digital prevention tools. Even when advanced platforms are technically available, their impact depends on the ability of citizens, clinicians, and policymakers to understand, trust, and use them in real decision-making contexts. Training materials, onboarding procedures, and user support mechanisms therefore represent essential components of implementation readiness, particularly in complex healthcare ecosystems where digital literacy, workflow integration, and institutional capacity may vary significantly.

1.3 Research Objectives and Paper Contribution

This paper examines the role of the ONCODIR digital ecosystem in supporting intelligent, secure, and prevention-oriented healthcare infrastructures. The analysis focuses on three core components: NELI, DEPO, and DELI. NELI supports citizen engagement by enabling users to monitor lifestyle factors and receive personalised prevention-oriented recommendations. DEPO supports clinicians by providing AI-enabled decision support and facilitating personalised counselling. DELI supports policymakers by transforming aggregated data and prevention indicators into evidence for public health planning.

The main research question addressed in this paper is: How can integrated digital health tools support multi-level decision-making and stakeholder engagement in colorectal cancer

prevention within smart healthcare ecosystems? To answer this question, the paper adopts an implementation-oriented analytical approach, drawing on the ONCODIR ecosystem as a case of digital public health infrastructure. The analysis considers how citizen-generated data, clinical intelligence, and policy analytics can be connected in a secure and interoperable framework.

The contribution of the paper is threefold. First, it frames CRC prevention as a smart healthcare challenge that requires coordination between individual behaviour, clinical practice, and public health governance. Second, it discusses how NELI, DEPO, and DELI illustrate a multi-stakeholder model for digital prevention, connecting citizens, healthcare professionals, and policymakers through complementary tools. Third, it highlights the importance of interoperability, FAIR data principles, ethical safeguards, and cybersecurity in the development of resilient digital health ecosystems. In addition, the paper considers training and user adoption as enabling factors for the successful implementation of digital prevention ecosystems, emphasizing that technological innovation must be accompanied by operational readiness and stakeholder capacity building. By positioning ONCODIR within the broader smart city and digital governance literature, the paper contributes to ongoing debates on how intelligent infrastructures can support sustainable, citizen-centred, and evidence-based public health systems.

2. Background and Related Work

2.1 Smart Healthcare Infrastructures and Digital Public Health

Smart cities increasingly depend on interconnected infrastructures that combine data, services, institutions, and citizens into integrated urban ecosystems. In this context, healthcare is no longer limited to hospitals or isolated clinical encounters, but becomes part of a broader digital public service infrastructure. Smart healthcare systems may include mobile applications, Internet of Things (IoT) devices, cloud-based platforms, data repositories, AI-enabled services, and dashboards for monitoring and decision-making. Previous research in the Smart Cities and Regional Development literature has emphasized the role of IoT-based healthcare services in enabling real-time monitoring and more responsive health interventions in smart city environments [3]. Similarly, studies on smart hospital governance show that digital transformation in healthcare requires not only technology, but also organizational readiness, infrastructure, interoperability, cybersecurity, and clear governance mechanisms [4].

Digital public health extends this logic by applying digital technologies to core public health functions such as prevention, surveillance, risk communication, health promotion, and policy planning. Rather than focusing only on individual treatment, digital public health aims to support population-level health outcomes through data-driven and preventive approaches [8,9]. This is particularly relevant for colorectal cancer (CRC), where prevention depends on long-term monitoring of behavioural risk factors, early detection, citizen awareness, and evidence-based resource allocation.

However, smart healthcare infrastructures also introduce new risks and governance requirements. The integration of multiple actors and systems increases the complexity of data flows and creates stronger dependencies on cybersecurity, privacy protection, and

institutional trust. Research on information security in healthcare highlights that digital health systems must protect sensitive information while maintaining availability, integrity, and usability [10]. Moreover, algorithmic public health systems raise ethical questions related to transparency, proportionality, and the balance between public benefit and individual rights [7]. Therefore, digital healthcare ecosystems must be designed as secure, interoperable, and citizen-centred infrastructures.

2.2 Participatory and Data-Driven Prevention Approaches

Prevention-oriented healthcare systems increasingly rely on participatory approaches, in which citizens, patients, clinicians, and policymakers are actively involved in the design and use of health interventions. In the case of CRC prevention, such participation is essential because many relevant risk factors are linked to daily behaviours, including diet, physical activity, alcohol consumption, smoking, and screening participation. Digital tools can support these processes by enabling self-monitoring, personalised feedback, and continuous communication between users and healthcare stakeholders.

The literature on mobile health indicates that digital interventions can contribute to cancer screening and early detection, especially when they combine reminders, educational content, risk communication, and user engagement mechanisms [11]. Nevertheless, user engagement remains a major challenge. Digital health applications often face declining use over time, and their effectiveness depends on usability, perceived usefulness, trust, accessibility, and the degree to which users feel that the technology responds to their needs [12]. For this reason, participatory design and co-creation are increasingly considered necessary for the adoption of digital health tools.

Data-driven prevention also requires reliable, reusable, and interoperable data. The FAIR principles — Findable, Accessible, Interoperable, and Reusable — provide an important foundation for structuring health-related data in a way that supports transparency, reproducibility, and secondary use [13]. In cancer prevention, FAIR data ecosystems can enable the integration of clinical, behavioural, demographic, and policy-related information, supporting both individual recommendations and population-level analysis. Within ONCODIR, the co-design process and the Open Data Bank reflect this orientation by connecting stakeholder requirements, structured data resources, and prevention-oriented analytics.

Participatory and data-driven approaches are therefore complementary. Participation ensures that prevention tools remain aligned with the needs, capacities, and expectations of users, while data-driven analytics supports evidence-based decision-making. Together, they create the conditions for prevention systems that are not only technically advanced, but also socially relevant, inclusive, and operationally usable.

2.3 AI and Decision Support in Preventive Healthcare

Artificial intelligence has become increasingly relevant in healthcare decision support, particularly in contexts where large volumes of heterogeneous data must be interpreted to inform clinical or policy decisions. AI-based clinical decision support systems can assist healthcare professionals by identifying risk patterns, summarising relevant information,

generating recommendations, and supporting personalised counselling. In preventive healthcare, such systems are particularly valuable because they can help transform behavioural and clinical indicators into actionable prevention strategies.

However, the adoption of AI-based decision support in healthcare depends on more than predictive performance. Recent systematic reviews show that clinician trust is influenced by explainability, transparency, usability, workflow integration, training, and the perceived reliability of recommendations [6,14]. Explainable AI is especially important in clinical contexts because healthcare professionals must understand the rationale behind recommendations before integrating them into practice [15]. AI tools should therefore support human judgement rather than replace it, especially in prevention-oriented settings where behavioural, social, and clinical factors must be interpreted together.

Decision support is also relevant beyond the clinical level. Policy analytics tools can support public health governance by aggregating data, identifying trends, comparing risk factors, and evaluating intervention outcomes. In smart healthcare ecosystems, the combination of citizen-facing tools, clinical dashboards, and policy analytics platforms enables multi-level decision-making. This approach is aligned with the broader movement toward intelligent public services, where data and AI are used to improve planning, responsiveness, and resource allocation while maintaining accountability and ethical safeguards.

For CRC prevention, AI-enabled and policy-oriented decision support can help bridge the gap between individual behaviour, clinical practice, and public health governance. The ONCODIR ecosystem reflects this direction by integrating citizen engagement through NELI, AI-based clinical support through DEPO, and policy analytics through DELI. This combination illustrates how digital health infrastructures can contribute to prevention-oriented, evidence-based, and cyber-resilient smart healthcare systems.

3. The ONCODIR Digital Ecosystem

3.1 System Overview and Architecture

The ONCODIR digital ecosystem is designed as a multi-stakeholder infrastructure for colorectal cancer prevention, connecting citizens, healthcare professionals, and policymakers through complementary digital tools. Its architecture follows a prevention-oriented logic in which behavioural, clinical, and population-level information can be collected, processed, interpreted, and reused to support decisions at different levels of the healthcare system. Rather than operating as isolated applications, the ONCODIR components are structured as an interconnected ecosystem in which citizen engagement, clinical counselling, and policy analytics are linked through shared data flows and common governance principles.

At the user-facing level, the ecosystem is organised around three main tools: NELI, DEPO, and DELI. NELI is the citizen-oriented mobile application, supporting lifestyle monitoring, risk awareness, and personalised prevention-oriented feedback. DEPO is the clinician-facing dashboard, enabling healthcare professionals to review relevant information and support personalised counselling. DELI is the policy analytics dashboard, designed to

support public health decision-making through aggregated indicators, visual analytics, and evidence-based policy insights. These tools correspond to the three main stakeholder groups identified in the ONCODIR co-design process: citizens/patients, clinicians, and policymakers.

From an architectural perspective, the ecosystem can be understood through four functional layers. The first layer is the data acquisition layer, which includes citizen-generated inputs, lifestyle indicators, questionnaire-based information, and other prevention-relevant data collected through digital interaction. The second layer is the data processing and analytics layer, where information is harmonised, aggregated, and transformed into meaningful prevention indicators. This layer includes risk stratification, data fusion, predictive analytics, and trustworthy AI-related assessment mechanisms. The third layer is the application and decision-support layer, represented by the interfaces through which citizens, clinicians, and policymakers interact with the system. The fourth layer is the governance and interoperability layer, which includes data quality, FAIR principles, metadata management, access control, ethical safeguards, and secure data exchange.

A central element supporting interoperability and reuse is the ONCODIR Open Data Bank. The Open Data Bank provides access to curated and FAIRified resources such as CRC-related risk factor datasets, country-level predictive analytics, policy intervention datasets, aggregated prospective data, CRC risk questionnaires, and nutritional guidelines. The Open Data Bank is also designed around a layered architecture that separates presentation, application, and data layers, supporting maintainability, controlled access, and structured data governance. This strengthens the role of ONCODIR not only as a technological platform, but also as a knowledge infrastructure for research, clinical interpretation, and policy-oriented analysis.

The architecture also reflects the participatory development approach of the project. End-user requirements were collected and refined through workshops, focus groups, prototype demonstrations, and structured feedback sessions involving the main stakeholder groups. This process informed the functional and non-functional requirements of the tools and supported the creation of an integrated system design covering databases, interfaces, communication flows, and data exchanges. As a result, the ecosystem aims to combine technical interoperability with user-centred design, ensuring that the digital tools respond to the practical needs of citizens, clinicians, and policymakers.

For the purpose of this paper, the ONCODIR architecture is discussed at a conceptual and implementation-oriented level. Detailed security configurations, internal endpoints, credentials, individual-level health data, and non-public technical specifications are not included. This approach preserves GDPR compliance and avoids exposing sensitive implementation details, while still allowing the system to be analysed as a model for secure, interoperable, and prevention-oriented smart healthcare infrastructures.

3.2 NELI: Citizen Engagement and Lifestyle Monitoring

NELI represents the citizen-facing component of the ONCODIR digital ecosystem and is designed to support colorectal cancer prevention through user engagement, lifestyle

monitoring, and personalised feedback. Its role is to bring prevention closer to the individual by enabling citizens to interact with digital health services outside traditional clinical environments. In this sense, NELI contributes to the development of smart healthcare infrastructures by extending prevention activities into everyday life and by supporting continuous interaction between users and the broader ONCODIR ecosystem.

The application is centred on the collection and interpretation of prevention-relevant information. These include both non-modifiable factors, such as age, biological sex, family history, genetic predisposition, and comorbidities, and modifiable factors, such as physical activity, sedentary behaviour, nutrition, alcohol consumption, smoking, socioeconomic context, and CRC awareness. The inclusion of such factors is important because CRC prevention depends not only on clinical risk assessment, but also on understanding behavioural and social determinants that influence long-term health outcomes.

From an implementation perspective, NELI supports the completion of structured questionnaires and the monitoring of lifestyle indicators relevant to CRC prevention. The questionnaire logic was developed through a collaborative and iterative process, using a risk factor matrix as a foundation and refining the questions to maintain both clinical relevance and user-friendly interaction. This approach allows citizens to provide information in a structured format while supporting future analysis, risk stratification, and personalised recommendations.

A central function of NELI is the delivery of personalised lifestyle recommendations. Within ONCODIR, such recommendations are intended to translate individual risk profiles into practical, targeted guidance for prevention and healthy living. The recommendation process was developed through a structured validation workflow involving clinicians and policy-related stakeholders. Recommendations were reviewed for clarity, accuracy, relevance, and delivery mode, including whether they could be sent directly to citizens or should first be reviewed by a healthcare professional through DEPO. This mechanism reflects the balance between citizen empowerment and clinical oversight, which is essential in prevention-oriented digital health systems.

NELI also plays an important role in stakeholder engagement and user-centred design. The application was presented and discussed in dedicated end-user sessions, including a citizen stakeholder session in which participants interacted with the prototype and provided structured feedback on usability and functionality. These activities helped refine the tool and ensured that the application responds not only to technical requirements, but also to user expectations and real-world adoption needs.

Beyond individual engagement, NELI contributes to the broader ONCODIR data ecosystem. Aggregated prospective data originating from the mobile application can support population-level insights across pilot contexts, while avoiding the exposure of identifiable personal data. In this way, NELI acts as both an engagement tool and a data source for evidence-based prevention, linking citizen-generated information with clinical decision support and policy analytics. This dual role strengthens the capacity of ONCODIR to support prevention strategies that are personalised, participatory, and scalable.

For the purpose of this paper, NELI is discussed only at a functional and conceptual level. No individual-level health data, identifiable user information, internal credentials, or sensitive implementation details are included. This is consistent with the GDPR-oriented and ethical framing required for digital health ecosystems and smart healthcare infrastructures.

3.3 DEPO: AI-Based Clinical Decision Support

DEPO represents the clinician-facing component of the ONCODIR digital ecosystem and is designed to support healthcare professionals in colorectal cancer prevention through AI-based counselling and decision support. Its main role is to assist clinicians in interpreting prevention-relevant information, reviewing risk-related outputs, and supporting personalised guidance for citizens. In this way, DEPO connects the citizen-oriented functionalities of NELI with professional medical oversight, ensuring that prevention remains both personalised and clinically responsible.

The need for such a tool is linked to one of the major challenges of prevention-oriented healthcare systems: the limited time available for personalised counselling in routine clinical practice. Healthcare professionals often face high workloads, while prevention requires sustained communication, behavioural guidance, and interpretation of multiple risk factors. AI-based clinical decision support systems can help address this gap by organising relevant information, highlighting patterns, and supporting the formulation of recommendations [6]. However, in healthcare, AI tools must be designed to support professional judgement rather than replace it. Trust, explainability, usability, and integration into existing workflows are essential conditions for adoption [14,15].

Within ONCODIR, DEPO functions as an intermediary layer between automated prevention logic and clinical validation. The co-design activities conducted in the project highlighted the importance of balancing user empowerment with clinical oversight. During the requirements and decision-point discussions, stakeholders considered issues such as automated recommendations, medical review, clinician notification protocols, risk-score visibility, tone of communication, and the timing of feedback to citizens. The results indicated support for clinician review of sensitive recommendations and for adapting communication to the user's risk level. This reinforces DEPO's role as a safeguard for responsible personalisation.

A key operational function of DEPO is the review of recommendations before they are delivered to citizens when clinical validation is required. The ONCODIR recommendation workflow distinguishes between recommendations that may be sent directly through NELI and those that should first be reviewed by a healthcare professional through DEPO. This process supports a human-in-the-loop model, where AI-enabled outputs and structured prevention logic are complemented by clinical expertise. Such an approach is particularly important in prevention, where recommendations may involve behavioural change, lifestyle adaptation, medical history, or risk communication.

DEPO also contributes to multi-level decision-making by transforming citizen-generated data and risk-related indicators into clinically interpretable information. Data collected through NELI, including questionnaires and lifestyle indicators, can be connected to risk stratification and recommendation processes. Clinicians can then use DEPO to support personalised counselling and guide users toward prevention-oriented actions. This linkage strengthens continuity between self-monitoring, clinical interpretation, and public health intervention.

From a trust and governance perspective, DEPO must operate within a secure and ethically controlled digital ecosystem. The ONCODIR architecture incorporates principles such as role-based access, GDPR compliance, FAIR data management, and trustworthy AI assessment. In addition, the project's trustworthy AI framework includes mechanisms for bias and fairness assessment, supporting transparency and expert review where adaptation may be required. These safeguards are relevant for clinical decision support because prevention recommendations must be not only technically accurate, but also fair, explainable, and aligned with user needs.

For the purposes of this paper, DEPO is analysed as a conceptual and functional component of the ONCODIR ecosystem. The discussion does not include individual health records, identifiable user information, internal dashboard screenshots, credentials, or detailed technical configurations. This ensures that the analysis remains compatible with ethical, GDPR, and cybersecurity requirements while still demonstrating how AI-based clinical decision support can strengthen prevention-oriented smart healthcare infrastructures.

3.4 DELI: Policy Analytics and Multi-Level Governance

DELI represents the policy-oriented component of the ONCODIR digital ecosystem and is designed to support evidence-based governance in colorectal cancer prevention. While NELI focuses on citizen engagement and DEPO supports clinician-centred decision-making, DELI addresses the needs of policymakers by transforming aggregated data, risk factor indicators, and predictive analytics into accessible insights for public health planning. Its role is particularly relevant in smart healthcare ecosystems, where prevention strategies require coordination across clinical, behavioural, economic, and administrative dimensions.

The development of DELI responds to the need for policy tools that can support prevention-oriented decision-making beyond descriptive epidemiology. During the ONCODIR co-design process, policymakers highlighted the importance of analysing incidence and prevalence trends over time, correlating epidemiological patterns with demographic and behavioural factors, and integrating economic or cost-related elements to support decisions on prevention interventions. This feedback illustrates that policy analytics dashboards must go beyond data visualisation and provide actionable intelligence for intervention planning, prioritisation, and monitoring.

At the data level, DELI is supported by curated and harmonised resources developed within the ONCODIR ecosystem. These include country-level CRC-related risk factor datasets, subgroup analysis outputs, policy intervention mappings, and predictive analytics results.

The Policy Intervention Dataset maps existing CRC and non-communicable disease prevention policies across EU Member States, identifying policy gaps, strong national initiatives, and transferable best practices. By connecting these policy mappings with analytical outputs, DELI contributes to a structured evidence base for comparing national contexts and informing public health strategies.

A central functionality of DELI is the provision of country-level predictive analytics. The platform supports the exploration of associations between population exposure to modifiable risk factors and future CRC incidence across different time horizons. The analytical approaches include statistical and machine learning models such as Generalized Additive Models, Linear Mixed Effects Models, and XGBoost, which are used to generate population-level projections and scenario-based insights. These outputs are intended to support exploratory and comparative analyses for policymakers, rather than direct causal interpretation or individual-level clinical decision-making.

DELI also strengthens multi-level governance by enabling policy actors to connect local or national prevention challenges with broader European evidence. This is important because CRC prevention strategies are influenced by differences in health systems, institutional capacities, demographic structures, cultural behaviours, and policy frameworks. Cross-country analytics can help identify common risk patterns, compare intervention approaches, and support more coherent policy dialogue. In this sense, DELI functions not only as a dashboard, but also as a governance support tool that can inform policy spaces, roundtables, and implementation roadmaps.

From a smart city perspective, DELI contributes to the transition from reactive public health administration to proactive, data-driven governance. By integrating aggregated behavioural indicators, clinical intelligence, and policy analytics, it supports the monitoring of prevention priorities and the evaluation of interventions over time. At the same time, the use of aggregated and privacy-preserving datasets ensures that policy-level analysis can be performed without exposing individual-level health information. This reinforces the role of DELI as a secure and scalable component of the ONCODIR ecosystem, supporting evidence-based public health decision-making while respecting ethical and GDPR-related constraints.

Overall, DELI complements NELI and DEPO by extending the ONCODIR ecosystem from individual and clinical prevention to population-level governance. Together, the three tools create a multi-level digital infrastructure in which citizens generate prevention-relevant data, clinicians interpret risk and support personalised counselling, and policymakers use aggregated evidence to design, monitor, and adapt prevention strategies.

3.5 Interoperability, FAIR Data Principles, and Secure Data Exchange

Interoperability is a central requirement for the ONCODIR digital ecosystem because the platform connects different actors, tools, and data flows across prevention-oriented healthcare processes. NELI, DEPO, and DELI serve different stakeholder groups, but their impact depends on the ability to exchange and interpret information in a coherent and secure manner. In this context, interoperability is not only a technical objective, but also a

governance condition that enables citizen-generated data, clinical interpretation, and policy analytics to contribute to a shared evidence base.

A key element supporting interoperability within ONCODIR is the adoption of FAIR data principles. The FAIR framework requires data to be Findable, Accessible, Interoperable, and Reusable, thereby improving transparency, reproducibility, and long-term value for research and policy [13]. In health-related ecosystems, FAIR principles are particularly important because data are often heterogeneous, sensitive, and generated across multiple institutional contexts. By applying FAIR-oriented practices, digital prevention platforms can improve the quality and usability of data while supporting secondary analysis, public health monitoring, and evidence-based decision-making.

Within ONCODIR, the Open Data Bank functions as a core infrastructure for FAIR-compliant data management and knowledge reuse. It includes curated resources such as CRC-related risk factor datasets, country-level predictive analytics outputs, subgroup analysis results, policy intervention datasets, aggregated prospective data, CRC risk questionnaires, and nutritional guidelines. These resources are structured to support researchers, clinicians, and policymakers while avoiding the exposure of identifiable personal information. The use of metadata, standardized data dictionaries, persistent identifiers, ontology alignment, and controlled access mechanisms improves both interoperability and reusability.

Semantic interoperability is further supported through ontology-based modelling. The ONCODIR CRC Risk Factor and Burden Ontology provides a structured representation of disease burden, behavioural risk factors, demographic dimensions, geographic information, and statistical associations. This semantic layer is important because it allows data elements to be interpreted consistently across tools and stakeholder contexts. For example, behavioural risk indicators collected or analysed in one part of the ecosystem can be connected to policy analytics or clinical interpretation through shared definitions and semantic structures. Such an approach strengthens the capacity of the ecosystem to transform heterogeneous health information into actionable knowledge.

Secure data exchange represents another essential dimension of the ONCODIR architecture. Since digital health ecosystems process sensitive and potentially health-related data, information flows must be governed by privacy-by-design and security-by-design principles. The Open Data Bank architecture applies controlled access mechanisms, including role-based access, token-authenticated service access, governance rules based on the principle of least privilege, and auditable logs. These mechanisms support secure collaboration while ensuring that access rights remain aligned with user roles and data governance responsibilities.

The system also addresses GDPR-related safeguards by prioritising anonymised and aggregated data where possible. In the context of retrospective and prospective data, the ONCODIR approach emphasises the minimisation of privacy risks through aggregation, removal of personal identifiers, and governance procedures intended to prevent direct or indirect re-identification. This is particularly relevant for public health analytics, where

aggregated evidence can support policy decisions without exposing individual-level health information.

From a smart city perspective, interoperability and secure data exchange are prerequisites for cyber-resilient public health infrastructures. Healthcare ecosystems increasingly depend on distributed digital services, and therefore must maintain data quality, system trust, privacy protection, and operational continuity. The ONCODIR model illustrates how prevention-oriented platforms can combine FAIR data management, semantic interoperability, access governance, and stakeholder-oriented interfaces to support resilient digital public health systems. In this way, interoperability becomes not only a technical feature, but a foundation for sustainable, secure, and evidence-based cancer prevention.

4. Implementation, Impact, and Adoption Perspectives

4.1 Impact on Citizens, Clinicians, and Policymakers

The ONCODIR ecosystem is designed to create impact across three interconnected stakeholder levels: citizens, clinicians, and policymakers. For citizens, the expected impact is linked to prevention awareness, lifestyle monitoring, and personalised engagement. Through NELI, users can interact with prevention-oriented information, complete structured questionnaires, monitor lifestyle indicators, and receive recommendations adapted to their risk profile. This supports a shift from passive participation in healthcare to active involvement in prevention practices, which is particularly relevant for colorectal cancer, where modifiable behaviours such as diet, physical activity, smoking, alcohol consumption, and screening participation can influence long-term risk.

For clinicians, the impact is associated with better use of structured data and more efficient prevention counselling. DEPO supports healthcare professionals by helping them interpret relevant information and review recommendations when medical oversight is required. This is important because prevention counselling is often constrained by limited consultation time and high workloads. By organising prevention-related information into a clinician-facing dashboard, DEPO can support personalised interaction without replacing professional judgement. This human-in-the-loop approach is consistent with the ONCODIR objective of maintaining the clinician-patient relationship while using digital tools to improve continuity and efficiency.

For policymakers, DELI provides a policy analytics perspective by enabling the analysis of aggregated indicators, risk factors, and intervention outcomes. Its impact lies in supporting evidence-based governance, allowing public authorities to identify prevention gaps, compare country-level or population-level patterns, and design more targeted public health interventions. This is especially relevant in multi-level governance environments, where prevention strategies must be adapted to national, regional, and local contexts. Together, NELI, DEPO, and DELI create a multi-stakeholder ecosystem in which individual-level engagement, clinical interpretation, and policy-level intelligence reinforce each other.

4.2 Training, User Adoption, and Operational Readiness

The implementation of digital prevention ecosystems depends not only on the technical availability of tools, but also on the ability of users to understand, trust, and apply them in real contexts. Training, onboarding, and operational support are therefore essential for transforming digital health platforms into usable public health infrastructures. This is particularly important in prevention-oriented systems, where users include heterogeneous groups with different levels of digital literacy, health literacy, institutional responsibility, and professional expertise.

In the ONCODIR context, training and user adoption are relevant for all three main stakeholder categories. Citizens require clear onboarding procedures, accessible language, and practical guidance for using NELI. This is particularly important for users with limited health literacy or digital skills. Clinicians require training that explains how DEPO supports counselling, how recommendations should be reviewed, and how the dashboard fits into existing workflows. Policymakers require guidance on how DELI can be used to interpret aggregated indicators, explore policy-relevant trends, and support intervention planning.

Operational readiness also depends on iterative feedback. ONCODIR co-design activities involved workshops, prototype demonstrations, structured questionnaires, and feedback sessions for the main tools, including NELI, DEPO, and DELI. This approach helps ensure that the system is not only technically functional, but also aligned with user expectations and implementation needs. In this sense, training materials and user support mechanisms should be understood as part of the system architecture: they create the conditions for adoption, trust, and long-term sustainability.

A further adoption challenge concerns institutional integration. Digital prevention tools must avoid creating parallel processes that increase the burden on healthcare professionals or public authorities. Instead, they should be integrated progressively through pilots, evaluation, and scale-up. This phased approach supports adaptation to local health-system constraints and allows the ecosystem to evolve based on user feedback, operational lessons, and policy priorities.

4.3 Cyber-Resilience, GDPR Compliance, and Ethical Considerations

Because the ONCODIR ecosystem operates in the field of digital health, cyber-resilience and data protection are central requirements. Healthcare data are highly sensitive, and prevention-oriented systems may involve behavioural, clinical, demographic, and lifestyle-related information. As a result, digital health infrastructures must be designed to protect confidentiality, integrity, availability, and accountability throughout the data lifecycle [10].

The ONCODIR approach addresses these requirements through privacy-by-design, security-by-design, and data governance principles. The Open Data Bank supports FAIR data management, controlled access, metadata governance, semantic interoperability, and role-based access mechanisms [13]. At the same time, GDPR-related safeguards require that personal data processing be minimised and that anonymised or aggregated data be prioritised whenever possible [16]. This is particularly important for policy analytics,

where meaningful public health insights can often be generated from aggregated datasets without exposing identifiable individual information.

Ethical considerations are also relevant for AI-enabled prevention systems. AI-based decision support must be transparent, explainable, and used in a way that supports human expertise rather than replacing it. In the ONCODIR ecosystem, this is reflected in the distinction between recommendations that may be delivered directly to citizens and those requiring clinician review before delivery. Such mechanisms help reduce the risk of inappropriate automation and reinforce accountability in prevention counselling.

Cyber-resilience should therefore be understood not only as a technical concern, but also as an organisational and ethical requirement. Secure authentication, access control, auditability, data minimisation, user training, and governance procedures all contribute to maintaining trust in digital health ecosystems. For smart city environments, where public services increasingly depend on interconnected infrastructures, these safeguards are essential for ensuring continuity, public acceptance, and responsible innovation.

4.4 Smart City and Public Health Policy Implications

The ONCODIR ecosystem illustrates how cancer prevention can be integrated into the broader development of smart healthcare infrastructures. In smart cities, public health services increasingly depend on data-driven coordination between citizens, healthcare institutions, technology providers, and public authorities. Digital prevention platforms such as ONCODIR can contribute to this transformation by connecting individual engagement with clinical decision support and policy analytics.

From a public health perspective, the ecosystem supports a transition from reactive healthcare to proactive prevention. Instead of relying only on clinical encounters or late-stage interventions, digital platforms can help identify risk patterns, promote healthier behaviours, and support earlier action. This is particularly important for CRC prevention, where behavioural risk factors and screening participation play a major role in reducing long-term disease burden.

From a governance perspective, DELI and the Open Data Bank support the use of aggregated evidence for policy planning. They can help policymakers compare prevention contexts, identify gaps, and support the scaling of successful interventions. The use of FAIR data principles and cross-country analytics can also improve learning between regions and Member States, enabling more coherent and adaptable prevention strategies.

Finally, the ONCODIR case highlights the importance of combining technological innovation with institutional readiness. Digital tools can only generate sustainable impact if they are accompanied by training, ethical safeguards, cybersecurity measures, and policy uptake mechanisms. In this sense, the ecosystem contributes to the development of secure, citizen-centred, and evidence-based digital public health systems. Its broader implication is that smart city healthcare infrastructures should not only collect and process data, but also support trust, prevention, inclusion, and accountable decision-making.

5. Conclusions and Future Work

This paper examined the ONCODIR digital ecosystem as a model for integrating citizen engagement, clinical decision support, and policy analytics in colorectal cancer prevention. The analysis focused on three complementary tools: NELI, which supports citizen participation and lifestyle monitoring; DEPO, which enables AI-based clinical decision support and personalised counselling; and DELI, which provides policy analytics for evidence-based public health governance. Together, these components illustrate how digital health ecosystems can connect individual behaviour, clinical interpretation, and population-level decision-making within smart healthcare infrastructures.

The main contribution of the paper is the positioning of colorectal cancer prevention as a multi-level digital public health challenge. Rather than approaching prevention only as a medical intervention, the ONCODIR ecosystem demonstrates the importance of combining behavioural data, clinical intelligence, policy-oriented analytics, and stakeholder engagement. This integrated approach supports the transition from reactive healthcare models toward proactive, prevention-oriented, and data-driven systems.

The paper also highlighted the importance of interoperability, FAIR data principles, secure data exchange, GDPR compliance, and ethical AI governance. These elements are essential for building trust in digital prevention ecosystems and for ensuring that health data can be used responsibly across different stakeholder contexts. In addition, training and operational readiness were identified as key adoption factors, since the successful implementation of digital tools depends on the ability of citizens, clinicians, and policymakers to understand and use them effectively.

Future work should focus on the continued validation of the ONCODIR tools in real-world pilot settings, with particular attention to usability, stakeholder acceptance, workflow integration, and measurable prevention outcomes. Further research should also explore how aggregated evidence generated by digital prevention ecosystems can inform national and regional cancer prevention strategies. Finally, the scalability of such ecosystems should be assessed in relation to cybersecurity requirements, institutional capacity, interoperability standards, and long-term sustainability within smart city and public health infrastructures.

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