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Medical genetics in Indonesia: development, challenges, and future priorities in a diverse middle-income archipelago

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Abstract

Medical genetics in Indonesia is emerging within a highly diverse and geographically complex archipelago. This review outlines current developments, persistent challenges, and future priorities for integrating genetics and genomics into the national health system. Indonesia's extraordinary ethnic diversity drives heterogeneous patterns of hemoglobinopathies, inherited metabolic disorders, and variable susceptibility to both infectious and non-communicable conditions, underscoring the urgent need for population-specific genomic strategies. Recent national initiatives, including the Indonesia National Genome Project and the Biomedical & Genome Science Initiative (BGSi), signal a growing commitment to precision medicine and genomic infrastructure in this rapidly developing country. Expanding genomic diagnostics, pharmacogenomics, and early precision oncology programs have strengthened clinical capabilities in selected urban referral centers. Nevertheless, access remains highly uneven due to workforce shortages, infrastructure gaps, and the high cost of advanced genomic testing. In oncology, the limited incorporation of genetic and genomic assays into the JKN–INA-CBG (Jaminan Kesehatan Nasional Indonesian Case-Based Groups) reimbursement framework further restricts equitable access, often shifting costs directly to patients. Furthermore, geographic challenges in this spread-out country remain substantial.

Key future priorities include large-scale population genome sequencing, systematic integration of genetics into primary healthcare, expansion and professionalization of genetic counseling services,

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development of robust functional disease models (including patient-derived organoids), and the establishment of translational research platforms. Aligning genomic innovation with national health financing, public health programs, and regulatory frameworks will be essential to ensure that precision medicine is implemented equitably, at scale, and with clinical impact across the Indonesian archipelago.

Keywords: Indonesia; medical genetics; genetic diversity; precision medicine; genome sequencing; universal health coverage

Highlights

- Indonesia's ethnic diversity drives unique genetic heterogeneity in Southeast Asia
- Universal Health Coverage (through JKN) reaches 98% of people in Indonesia but genomics access remains limited
- National Genome Project and organoid platforms promise precision medicine application to all
- Genetic counseling and prenatal diagnosis need strong primary healthcare integration

1 Introduction

Medical genetics, defined as the clinical and laboratory discipline concerned with the diagnosis, management, and counseling of individuals with genetic disorders, as well as population-level risk assessment, is increasingly important in contemporary healthcare systems. Its significance spans risk prediction and prevention, identification of genetic bases of both common and rare diseases, personalized treatment, and informed reproductive decision-making. Together with genome-wide technologies and advanced bioinformatics, medical genetics provides the foundation for precision medicine [1–3].

Medical genetics in Indonesia is an evolving field shaped by the country's vast ethnic diversity, large population, geographically dispersed territory, and a unique spectrum of inherited and congenital disorders. A previous review by Ariani et al. summarized the early landscape of genetics and genomic medicine in Indonesia [4]. Since then, major national initiatives such as the National Genome Project and the Biomedical & Genome Science Initiative (BGSi) have transformed the field, warranting this updated review. Here, we summarize current advances, challenges, and future directions of medical genetics in Indonesia, with emphasis on clinical practice, research capacity, and public health integration.

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Medical genetics is not evenly developed globally, with low- and middle-income countries (LMICs) facing substantial structural, economic, and workforce-related barriers. Although Indonesia has recently been formally classified as an upper-middle-income country (UMIC) [5], in several research and healthcare domains, it continues to share characteristics with LMICs. This intermediate position makes Indonesia a particularly informative case study for understanding how medical genetics can be scaled within transitioning healthcare systems in Asia.

2 Indonesia's heterogeneous population composition

Indonesia is the 3rd most populous country in Asia, with 285 million inhabitants, and the 5th largest country, with 1.81 million km² [6]. On the other hand, the country ranks only 22nd in population density, with 158 inhabitants per km², even though its capital, Jakarta, has a population density exceeding 15,000 inhabitants per km², placing it among the most densely populated urban centers worldwide. This remarkable contrast is due to Indonesia’s status as the world's largest archipelago, comprising over 17,000 islands. As a result, striking differences exist among inhabitants across the country's numerous islands. [Figure 1A, 1B]. The enormous territory, coupled with the burdensome geographical composition, poses significant challenges for the Indonesian Government in ensuring equitable access to high-quality, easily accessible healthcare facilities for the diverse population. Indonesia's position as an island nation linking mainland Asia and Oceania has produced extensive human genetic diversity, with multiple maternal and paternal lineages detected across its archipelago [7]. In the last population census (2020), the Central Bureau of Statistics in Indonesia registered over 1300 ethnic groups, with more than 700 languages and dialects spoken in the country [8].

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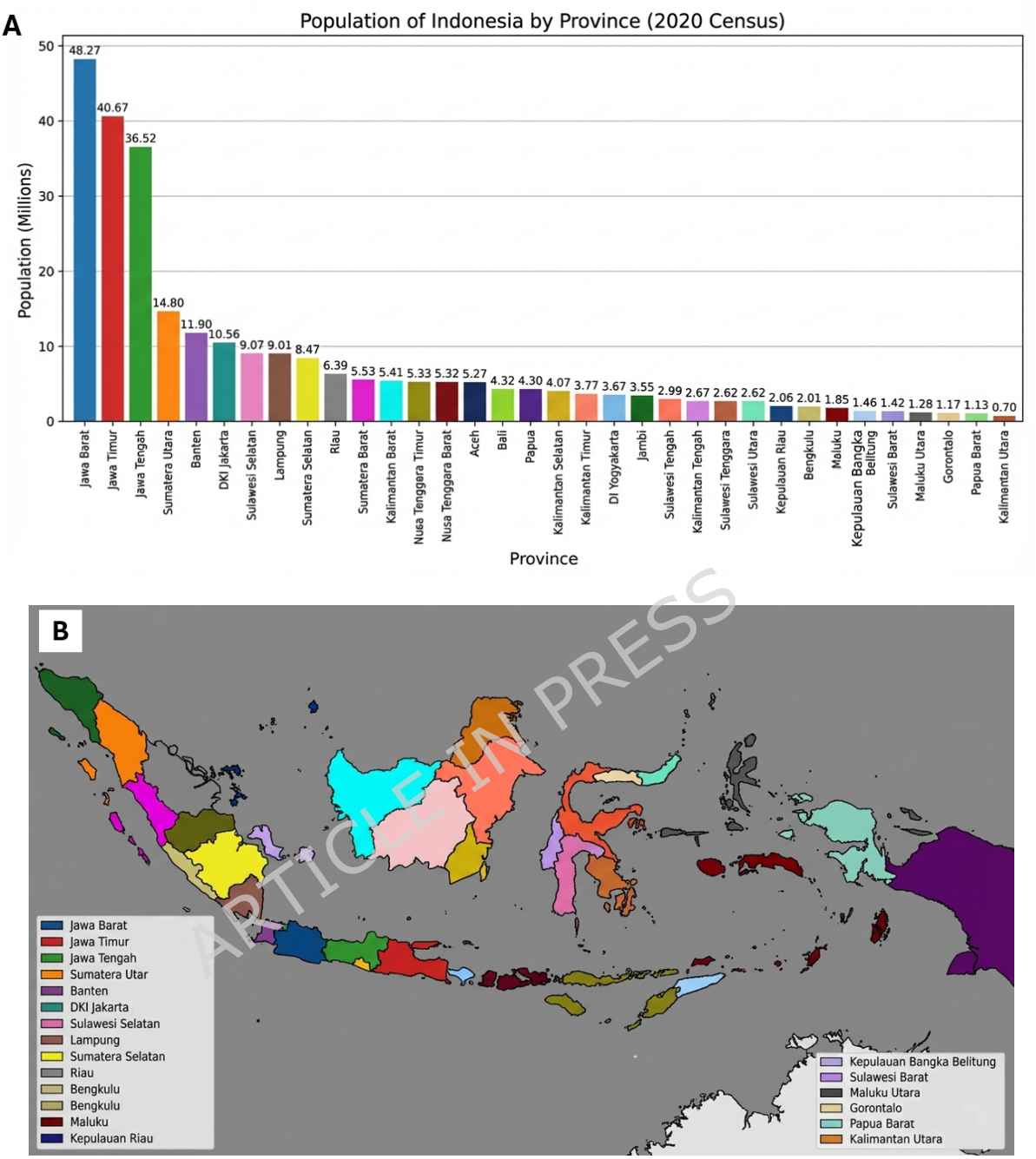


Figure 1. Population Distribution Across Indonesian Provinces: [A] Vertical bar chart showing the population of Indonesia's provinces according to the 2020 National census, and [B] a map of the country, with each color representing a different province. Population statistics were extracted from [8].

3 Regional and ethnic variation in genetic and infectious diseases

The country's vast ethnic diversity underscores a mosaic of congenital and sporadic disorders [Table 1]. Hemoglobinopathies, such as α/β-thalassemia and Hemoglobin E disease (HbE), reflect this population mosaicism pattern. Indeed, HbE is more prevalent in western Indonesia and among

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populations with Austroasiatic ancestry, while α and β-thalassemia variants differ across islands [9, 10]. This heterogeneity has direct implications for screening strategies, carrier detection, and prenatal programs. Additionally, geographic clustering of certain congenital anomalies has been reported in Indonesia, partly due to founder effects, consanguinity in specific regions, and under-recognized rare disorders. Therefore, carrier screening protocols and prenatal testing need to be designed regionally [4].

The current state of thalassemia across Southeast Asia, particularly in Indonesia, represents a substantial public health concern. Indonesia has one of the highest burdens of thalassemia in Southeast Asia, with an estimated 6–10% carrier frequency for β-thalassemia in certain regions and over 7,000 registered transfusion-dependent patients, many of whom lack access to optimal chelation therapy [11].

Dissimilarities among ethnic groups reflect a differential set of DNA variants across the population, causing variable rates of host susceptibility and immune response against diseases like tuberculosis, with incidence rates often reported in the hundreds per 100,000 population [12, 13], and dengue fever, with tens of thousands to over 100,000 reported cases annually [14, 15, 16].

Disease / Condition	Prevalence in Indonesia	Mode of Inheritance	Major Genetic Variants Reported	Clinic
β-Thalassemia	Carrier freq. 3–10%; ~2,500 affected births/year	Autosomal recessive	IVS-I-5 (G>C), CD26 (HbE), IVS-I-1, IVS-I-2, CD35, CD19; >12 variants in East Java alone	TDT, he skeletal thal/HbE to severe
α-Thalassemia	Carrier freq. 2.6–11%; varies by region/ethnicity	Autosomal recessive	Deletional (--SEA, -α3.7, -α4.2); non-deletional Hb Adana (Cd59, α2) up to 16% in some populations	Silent ca disease; Bart's) i
Hemoglobin E (HbE)	Higher prevalence in western Indonesia and Austroasiatic-ancestry populations	Autosomal recessive (codominant)	HBB c.79G>A (Cd26, GAG>AAG); aberrant splicing in exon 1	Heteroz asympto mild mic HbE/β-t transfus anemia

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Disease / Condition	Prevalence in Indonesia	Mode of Inheritance	Major Genetic Variants Reported	Clinic
G6PD Deficiency	0–20% (heterogeneous); majority of sites <5%; up to 25% in some eastern populations	X-linked recessive	Viangchan (p.V291M), Canton (p.R459L), Vanua Lava (p.L128P) in western Indonesia; distinct pattern in eastern populations	Acute h triggere (drugs, i jaundice in sever
Tuberculosis (TB)	~354/100,000 population (high endemic burden)	Polygenic susceptibility (infectious disease)	VDR polymorphisms (FokI, ApaI, BsmI, TaqI); JAG1, TXNDC4, CCL17 (Indonesian GWAS cohort); CD209 variants	Pulmona extrapul ethnic g differen
Dengue Fever	Tens of thousands to >100,000 cases/year; all 4 serotypes circulate	Polygenic susceptibility (infectious disease)	MICB rs3132468 (DSS risk); PLCE1 rs3740360 (DHF in secondary infection); TLR and CD209 variants	Ranges to dengu dengue (DHF), syndrom
Type 2 Diabetes Mellitus (T2DM)	~10.6% prevalence (2018 national survey); urban-rural disparity	Polygenic/multifactorial	TCF7L2, KCNJ11, KCNQ1, SLC30A8, CDKAL1; ancestry-adjusted PRS under development for Indonesian populations	Hypergl resistanc renal, a complic
Stroke & Cerebrovascular Disease	~16.1/1,000 population (Sleman District study); major contributor to disability	Polygenic/multifactorial	Hypertension- and lipid-associated loci; population-specific data limited; familial forms (CADASIL: NOTCH3; MELAS: mtDNA)	Ischemi stroke; a hyperter dyslipid
Metabolic Syndrome	Prevalent in urban populations; linked to central obesity and dietary transition	Polygenic/multifactorial	FTO, PPARG, ADIPOQ variants; under-studied in Indonesian cohorts	Central hypertri HDL, hy hypergly
Depression & Anxiety	High prevalence (23.6% depression in national sample; Peltzer & Pengpid 2018); childhood adversity key risk factor	Polygenic/multifactorial	SLC6A4 (5-HTTLPR s-allele; higher frequency in East Asian populations); BDNF Val66Met; FKBP5 variants; population-specific data in Indonesia limited	Major d generali post-trau associat socioeco childhoo

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Table 1. Genetic and infectious diseases with documented genetic susceptibility reported in Indonesia: Summary of genetic and infectious diseases with documented or putative genetic susceptibility components reported in Indonesia. For each condition, estimated prevalence in the Indonesian population, mode of inheritance, major genetic variants identified in Indonesian or Southeast Asian cohorts, principal clinical manifestations, and current clinical management strategies are provided. Prevalence data are derived from national surveys and peer-reviewed literature [9 - 22]. For polygenic conditions, variants listed represent those most consistently reported in Asian or Indonesian cohorts; population-specific data for Indonesia remain limited for several entries. Abbreviations: TDT, transfusion-dependent thalassemia; HSCT, hematopoietic stem cell transplantation; DHF, dengue hemorrhagic fever; DSS, dengue shock syndrome; DOTS, directly observed treatment, short-course; PRS, polygenic risk score; VDR, vitamin D receptor.

Moreover, variation in the genetic profile among Indonesians also affects fluctuations in incidence rates of other pathologies, namely: type 2 diabetes [17], stroke and associated risk factors [18], metabolic syndromes [19], depression and anxiety [20]. Glucose-6-phosphate dehydrogenase (G6PD) deficiency rates are also notably high, with some populations in the country reaching up to 25% affected [21, 22], making it the most common enzyme deficiency disorder in Indonesia. The high prevalence of G6PD deficiency is largely explained by evolutionary and population genetic factors. This condition has been maintained through balancing selection, as partial enzyme deficiency provides protection against *Plasmodium falciparum* severe malaria, a phenomenon observed in many malaria-endemic regions [23, 24]. Studies conducted in eastern Indonesia have demonstrated considerable heterogeneity in the distribution of G6PD variants among local populations, reflecting the country's complex demographic history and ethnic diversity [22]. Given the complexity of Indonesia's genetic landscape, assumptions about global rates in the country are, at best, uncertain.

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4 Healthcare in Indonesia: milestones achieved and current status

Decentralization reforms in the late 1990s and early 2000s shifted healthcare delivery to local governments, improving responsiveness in some areas but creating major regional disparities, fragmented financing, and high out-of-pocket costs. National health priorities focused on infectious diseases and basic public health, with minimal investment in biomedical research, particularly in genetics and genomics [25]. Although higher education and research capacity expanded, genetic research remained limited, fragmented, and largely confined to a few urban centers.

To address the large and fragmented territory, Indonesia's healthcare system was further decentralized in 1999, transferring significant administrative responsibility for healthcare delivery to local governments, resulting in steady improvements [25]. Unfortunately, the country faced a

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significant health crisis, with only half the population covered by health insurance, thereby worsening health disparities across populations [26]. To overcome such difficulties, the Indonesian government introduced important reforms in 2014 aimed at providing high-quality healthcare to all inhabitants. This universal health insurance program was based on a central scheme called Jaminan Kesehatan Nasional (JKN). Even though the initial target was missed (in 2019), health coverage fortunately continues to increase. It was reported that, as of 31 December 2024, 98.45% of Indonesians were registered in the National Health Insurance (JKN) programme [27]. The impact of the JKN scheme is also remarkable, lowering out-of-pocket expenses to 27.5 percent of current health expenditure [28]. Indonesia's Health Transformation Agenda (2022 onward) has placed primary healthcare (PHC) at the center of its Universal Health Coverage (UHC) strategy, aiming to strengthen frontline services and balance patient loads across facilities to improve access and quality under the JKN system [29]. A graphic summary of the development of healthcare in Indonesia is shown in Figure 2.

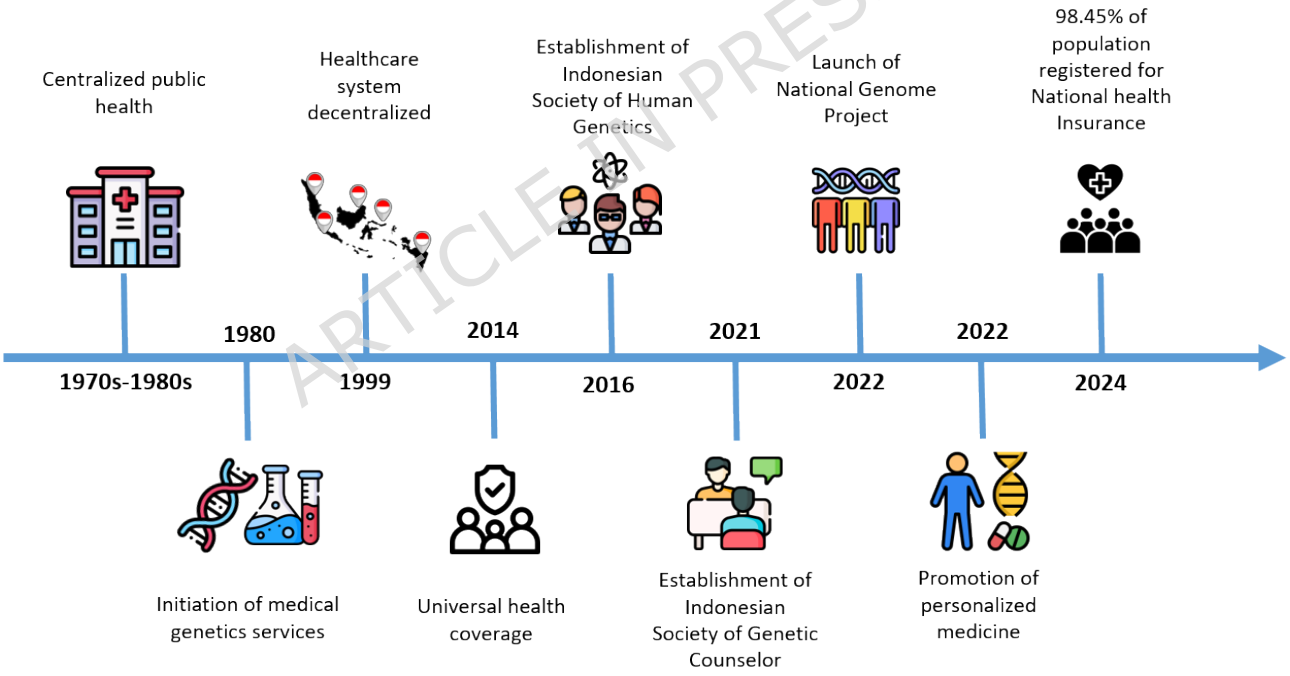


Figure 2. Key Milestones in the Evolution of Healthcare and Genomics in Indonesia: Over the past five decades, Indonesia's healthcare system has undergone substantial structural and policy transformations, evolving from a fragmented, under-resourced framework into one increasingly oriented toward universal health coverage. Genomics has followed this trend in parallel, with major improvements achieved.

5 Development of medical genetics services in Indonesia

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Medical genetics services in Indonesia were initiated in the 1970s, with the introduction of chromosome analysis and other basic cytogenetic techniques in university and hospital laboratories [30]. Due to low prioritization, limited workforce, and a lack of proper infrastructure, research in this area remained limited for some decades. In 2016, the Indonesian Society of Human Genetics was established to help professionals and advocate for formal recognition in Indonesia's healthcare system [4]. Private institutions and universities were fundamental to advancing genetic research, such as the Eijkman Institute and the Indonesian Institute of Sciences. Notable projects started in recent years aim to collect data that can contribute to research, such as the BGSI [31]. This initiative aimed to collect and sequence 10,000 Indonesian human genomes to map variant data for priority diseases, as part of a proof-of-concept phase, a target that was achieved in 2025. The project is still ongoing, with the government also planning longer-term goals [32]. To better illustrate the progress achieved since the previous comprehensive review by Ariani et al. in 2017, Table 2 provides a comparative summary of key developments across multiple domains of medical genetics in Indonesia over the past decade.

Domain	Then (Ariani et al., 2017)	Now (2026)
National genomics infrastructure	Limited to Eijkman Institute and a few university labs	BGSi established (2024); hub-and-spoke model; domestic NGS capacity
Genome sequencing capacity	Research-focused; no national program	National Genome Project: 10,000 genomes completed; target 400,000 by 2030
Genetic counselling	No formal training; limited awareness	Master's programs at Diponegoro & YARSI; ISGC established (2021)
Pharmacogenomics	Minimal clinical integration	Pilot programs in referral centres; population-specific pharmacogene data emerging
Precision oncology	Limited to research settings	*EGFR* testing in NSCLC; multigene panels for hereditary cancers; JKN reimbursement gaps remain

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Carrier screening	Fragmented; no national policy	Regional thalassemia screening; NIPT pilot programs
Policy & regulation	No national genomic framework	BGSi formalized (2024); ethical and data protection frameworks under development
Public health integration	Minimal	JKN covers 98.45%; primary healthcare (PHC) as entry point for genomic services

Table 2. Major developments in medical genetics and genomic medicine in Indonesia over the past decade: Comparison between the landscape described by Ariani et al. (2017) and the current status (2026), highlighting progress in genomic infrastructure, clinical services, research capacity, national policies, and healthcare integration.

6 Current state of clinical genetics and professional practice

Established in 2021, the Indonesian Society of Genetic Counsellors (ISGC) supports the development of genetic counselling professionals and promotes cooperation across healthcare settings [33]. A forum for Genetic Counsellors in Indonesia was established to share knowledge and experiences, to help patients and families understand genetic conditions, inheritance patterns, diagnostic options, and preventive strategies. Efforts to build workforce capacity in medical genetics have included academic programs and training. Notably, Masters' programs in Genetic Counselling at the Faculty of Medicine, Diponegoro University, as well as at YARSI University, were established through long-standing international collaboration (e.g., with Radboud University, The Netherlands) [33]. As of 2024, approximately 140 genetic counselling alumni had been recorded in Indonesia, primarily through the Master's-level training programs established at Diponegoro University and, more recently, YARSI University. In 2022, with the establishment of the Biomedical Genome Science Initiative (BGSI) for Precision Medicine, the Ministry of Health announced a healthcare transformation strategy that positions genomics science as a key part of the new Indonesian healthcare system [31], with the initiative formalized in 2024 [34]. The initiative operates through a hub-and-spoke model linked to a centralized biobanking and sequencing facility, enabling hospital-based recruitment of participants [34]. In 2025, a pilot program targeting the general population was also initiated to complement hospital-based data

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collection [35]. This initiative arose from the COVID-19 pandemic, in which genomics and molecular biology played a crucial role in disease control [Figure 2].

Centers such as the Human Genetics Research Cluster (HGRC) at medical faculties focus on chromosomal analysis, microarray analysis, gene mutation analysis, and neonatal screening for congenital and metabolic disorders. Such capabilities are foundational for clinical genetic diagnostics and highlight emerging research infrastructure within Indonesian institutions [36].

As previously mentioned, the Eijkman Institute was one of the leading research centers in Indonesia. Advanced diagnostic services have been developed for several diseases, including Spinal Muscular Atrophy (SMA), Duchenne Muscular Dystrophy (DMD), achondroplasia, Down Syndrome, Klinefelter syndrome, Turner syndrome, Disorders of Sexual Development (DSD), Prader–Willi syndrome and/or Angelman syndrome. Moreover, the Institute provides preconception counselling and prenatal diagnostic services. The forensic unit of the Institute also conducts paternity and maternity tests, using DNA profiles for both perpetrators and Disaster Victim Identification (DVI). The Eijkman Institute became subordinate to the National Research and Innovation Agency (BRIN) in 2021, which led to the dismissal of most researchers at the Eijkman Molecular Biology Research Center, with several laboratories moving to other research centers [37].

Mandaya Royal Hospital Puri has established a specialized Neuromuscular Center, described as the first of its kind in Indonesia. The center integrates advanced diagnostic technologies and an on-site DNA Genetic Laboratory that enables genetic testing for neuromuscular disorders previously available only abroad. These services support the diagnosis of a wide spectrum of conditions ranging from common nerve and muscle disorders to rare genetic neuromuscular diseases including Facioscapulohumeral Muscular Dystrophy (FSHD), Pinched Nerve (HNP), Migraine, ALS, Guillain Barré Syndrome and Myasthenia Gravis. The center is equipped with state-of-the-art diagnostic modalities including Advanced Single Fiber Electromyography (EMG), Evoked Potential Testing, Neuro Sensitive MRI, and an on-site DNA genetic testing laboratory. The hospital has also partnered with foundations (e.g., Widaya Foundation) to subsidize access to rare genetic tests, thereby overcoming barriers that previously required patients to travel overseas [38, 39].

7 Pharmacogenomics and polygenic risk scores in Indonesia

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Personalized medicine is considered one of the most prominent approaches in healthcare globally [40]. It integrates environmental, genetic, and lifestyle information to enable tailored prevention, diagnosis, and treatment strategies, thereby maximizing therapeutic benefits and minimizing potential harm. Advances in next-generation sequencing (NGS) technologies and bioinformatics have made it feasible to rapidly and cost-effectively interrogate millions of DNA variants, thereby enabling comprehensive genomic profiling for clinical decision-making [41]. In Indonesia, personalized medicine has been promoted as part of the modernization of the healthcare system since 2022, following the establishment of the BGSi. Collaborations with industry partners, including Illumina, reflect ongoing efforts to upgrade genomic capabilities and enable personalized diagnostics and treatments through accessible NGS platforms [42].

Pharmacogenomics represents a fundamental component of personalized medicine, exploring how genetic variation influences drug metabolism, efficacy, and toxicity. Indeed, it has been extensively demonstrated that variants in genes encoding drug-metabolizing enzymes, transporters, and receptors can markedly influence responses to a wide range of medications. In Indonesia, pharmacogenomics is becoming increasingly integrated into clinical practice through personalized care initiatives at referral centers such as RSU Royal Prima in Medan, where patients can receive genetic information to tailor medication choices and reduce adverse drug reactions [43]. Pharmacogenomics and nutrigenomics testing services were launched at RSU Royal Prima Medan in June 2025 through a collaboration with Global Precision Diagnostics. Publicly available reports document clinician training and patient consultations; however, cumulative patient numbers and hospital-specific outcomes, including reductions in adverse drug reactions, have not yet been published [44]. International evidence from the European PREPARE implementation study suggests that genotype-guided prescribing using a 12-gene panel may reduce clinically relevant adverse drug reactions by approximately 30%; however, comparable outcome data have not yet been reported from RSU Royal Prima Medan [45].

Recent studies have provided important insights into the representation of clinically relevant pharmacogenetic variants distribution within the Indonesian population. A multi-gene pharmacogenomic panel including clinically relevant pharmacogenes such as *CYP2C9*, *CYP2C19*, *CYP2D6*, and *SLCO1B1* has been validated across major ethnic groups in Indonesia and Singapore, supporting the feasibility of pharmacogenomic approaches in Southeast Asia [46]. Furthermore, population-specific analyses from Yogyakarta city, located on the island of Java,

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have provided initial insights into the frequency of key pharmacogenetic variants, affecting drug response, emphasizing the need for locally representative genomic resources to guide future clinical applications in Indonesia [47]. It should also be emphasized that translating pharmacogenomic discoveries into routine clinical practice requires overcoming challenges related to population diversity, clinical validation, healthcare infrastructure, and equitable access to genomic testing [48].

Although clinical implementation is still in its early stages, population-specific genomic research is progressing. A 2025 study on ancestry-adjusted polygenic risk scores (PRS) for obesity in the Indonesian population demonstrated that aggregation of multiple common genetic variants can improve risk prediction when models are tailored to local ancestries. This approach addresses the limitation of most PRS models, which are derived from European cohorts and perform suboptimally in diverse populations [49]. A project involving BINUS University and PT Genetics Indonesia developed a PRS model for hereditary cancer screening by integrating allelic variant data representative of Asian populations, including Indonesian samples, into a locally used DNA testing module [50]. The Indonesian PRS efforts are part of a broader issue in global genetic epidemiology: PRS models developed in one ancestry often perform poorly in others due to differences in allele frequencies, linkage disequilibrium patterns, and genetic architecture across populations. This limitation is not unique to Indonesia but is seen across many underrepresented groups in East Asia [50, 51]. The following table (Table 3) summarizes the main pharmacogenomic and polygenic risk score studies and initiatives relevant to the Indonesian population, highlighting the populations investigated, genetic markers, potential clinical applications, and principal findings.

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Reference	Study population	Genes / genetic variants	Clinical relevance / potential application	
Kothary et al. [46]	Indonesian and Singaporean populations representing major ethnic groups	*CYP2C9, CYP2C19, CYP2D6,* and *SLCO1B1*; 18 SNPs and 2 *CYP2D6* CNV markers	Pharmacogenomic testing and prediction of drug response and adverse drug reactions	Th ro cli *1 re

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Reference	Study population	Genes / genetic variants	Clinical relevance / potential application	
Nugrahaningsih et al. [47]	Yogyakarta population, Indonesia. 190 individuals	Clinically relevant variants in *CYP2C9, CYP2C19, CYP2D6,* and *SLCO1B1*	Population-specific pharmacogenomic profiling and genotype-guided prescribing	Hi *C* re *C* sp
Siswanto et al. [49]	~2,800 Indonesian individuals	Multiple common variants contributing to obesity susceptibility	Obesity risk prediction	An cla co
BINUS University [50	Indonesian genetic samples and Asian population variant data	Multiple variants associated with hereditary cancers	Hereditary cancer risk screening	A re de im m

Table 3. Pharmacogenomic and polygenic risk score studies relevant to the Indonesian population: Summary of studies investigating pharmacogenetic variation and polygenic risk scores in Indonesian populations, including study populations, genetic markers, potential clinical applications, and main findings**.**

8 Genetics and genomics in oncology practice in Indonesia

The application of genetic and genomic technologies in oncology is increasingly recognized as a critical component of precision medicine in Indonesia. Recent national efforts to harness cancer genomic big data and clinical sequencing have begun to support more individualized cancer care, although their integration into routine practice remains uneven [52].

Molecular profiling is now being utilized for both hereditary cancer risk assessment and therapeutic decision-making. Germline testing for hereditary cancer syndromes, particularly involving *BRCA1/2* and other high- and moderate-penetrance genes, has been introduced in selected academic and referral centers, and recent multigene panel studies among Indonesian familial cancer cohorts have identified pathogenic variants in *BRCA1, BRCA2, PALB2, MUTYH, RAD51D, VHL, ERCC4, and RB1* [53]. In parallel, somatic mutation testing, most notably *EGFR* and other oncogenic drivers in non-small-cell lung cancer (NSCLC), has been incorporated into workflows at tertiary cancer hospitals, where real-time PCR and next-generation sequencing

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(NGS) of tissue and circulating tumor DNA are used to guide targeted therapy selection [54]. Recent genomic studies of Indonesian lung adenocarcinoma cohorts have revealed substantial heterogeneity in the *EGFR* mutational landscape, including uncommon variants that may influence therapeutic decision-making. These findings underline the crucial value of population-specific molecular datasets to support more effective targeted treatment strategies in Indonesian patients [55]. Additional tumor types, such as colorectal and nasopharyngeal cancer, have also been subjected to genomic and epigenomic characterization, demonstrating the feasibility of broader molecular profiling in the Indonesian setting [56, 57].

Despite these advances, the implementation of precision oncology in Indonesia remains at an early stage and is characterized by substantial structural and economic barriers. Access to comprehensive genomic profiling, including NGS-based multi-gene panels, is largely confined to major urban centers and private or national referral institutions that possess the necessary laboratory infrastructure [50]. A key limiting factor is the high cost of testing, as most advanced genomic diagnostics and companion tests are not yet fully reimbursed under the JKN scheme; similar reimbursement gaps have been demonstrated for high-cost cancer services such as chemotherapy, underscoring broader challenges in integrating complex technologies into the INA-CBG payment system [58]. Consequently, many patients must bear substantial out-of-pocket costs, restricting equitable access and limiting widespread clinical adoption of precision oncology approaches.

In addition to cost constraints, several system-level challenges impede the effective deployment of oncology genomics. These include limited numbers of trained molecular pathologists, clinical geneticists, and genetic counsellors, as well as a shortage of bioinformaticians capable of handling and interpreting high-throughput sequencing data [59]. Similar barriers have been reported for the implementation of pharmacogenetics and genomic medicine in low- and middle-income countries, where workforce capacity, infrastructure requirements, economic sustainability, and integration into healthcare systems remain major challenges [60]. Variability in laboratory quality standards and the absence of nationally harmonized guidelines for genomic testing contribute to heterogeneity in test menus, platforms, and reporting practices across institutions. Furthermore, the incorporation of genomic information into routine clinical decision-making remains inconsistent, reflecting gaps in clinicians' familiarity with test indications and result interpretation, and the lack of robust, population-specific genomic databases for Indonesian cancer patients [61].

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Nevertheless, ongoing national initiatives are expected to accelerate the development of precision oncology over the coming years. The Indonesian National Genome Project and BGSi include programs focused on cancer and aim to generate large-scale genomic and multi-omics data on the Indonesian population, supported by local high-throughput sequencing platforms [62]. As of early 2026, the BGSi has generated genomic data from over 12,000 participants, with initial variant frequency reports for clinically actionable genes now available for the Javanese, Sundanese, and Batak populations. The establishment of domestic sequencing and bioinformatics capabilities has the potential to reduce costs and turnaround times, while collaborative efforts to use open-access cancer genomic resources may help bridge current data gaps and support translational research [56]. In the long term, integrating oncology-focused genomic services into the JKN framework, supported by clear national guidelines and population-specific evidence on clinical utility and cost-effectiveness, will be essential to ensure broader accessibility and meaningful clinical impact of precision oncology in Indonesia [56].

9 The future of medical genetics in Indonesia

The future of genetic and genomic medicine in Indonesia is closely tied to ongoing national initiatives, the expansion of clinical capacity, and technological innovation. The Indonesian National Genome Project and BGSi aims to sequence 400,000 genomes over the next five years, providing a foundational reference for population-specific variant frequencies. Such data are expected to enhance the accuracy of polygenic risk scores (PRS), pharmacogenomics guidance, and facilitate the identification of rare Mendelian variants across Indonesia's ethnically diverse populations.

Beyond large-scale sequencing, strategic investments should prioritize innovative functional models to study rare genetic diseases in the Indonesian context. The establishment of patient-derived organoid platforms, from individuals with undiagnosed neurodevelopmental, metabolic, or neuromuscular disorders, would enable variant interpretation, drug screening, and mechanistic studies that are currently lacking for underrepresented populations. Given Indonesia's high burden of thalassemia, G6PD deficiency, and regionally clustered congenital anomalies, organoid-based disease modeling could bridge the gap between genomic findings and clinical translation.

Beyond large-scale sequencing, strategic investments should prioritize innovative functional models to study rare genetic diseases. The establishment of patient-derived organoid platforms

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[63] would enable variant interpretation, drug screening, and mechanistic studies that are currently lacking for underrepresented populations.

This approach is particularly pertinent for middle-income countries like Indonesia. By utilizing locally sourced patient-derived cells, organoid models can mirror the unique genetic architecture of the Indonesian population, offering a more predictive and cost-effective alternative to traditional animal models or European-derived cell lines for disease modeling [63]. Evidence of this potential is already emerging: Indonesian institutions are actively developing organoid platforms, including liver organoids as bridging therapy for liver failure and 3D patient-derived co-culture organoids for precision oncology applications. Such initiatives demonstrate the feasibility and clinical relevance of these advanced models within the local research ecosystem.

Given Indonesia's high burden of thalassemia, G6PD deficiency, and regionally clustered congenital anomalies, organoid-based disease modeling could bridge the gap between genomic findings and clinical translation. The development of national organoid core facilities, as already seen with recent research funding and collaborative projects, represents a strategically cost-effective investment, generating reusable disease models that can be used for variant interpretation, drug screening, and mechanistic studies at a fraction of the cost of large-scale clinical trials.

Concurrently, strengthening genetic counseling services is essential. Despite the establishment of the Indonesian Society of Genetic Counsellors (ISGC) and master's programs, access remains concentrated in urban academic centers. Future efforts should integrate certified genetic counselors into primary healthcare (PHC) under the JKN scheme, develop tele-counseling for remote islands, and establish national certification and continuing education pathways. Prenatal diagnosis services are currently limited to a few referral hospitals. They require expansion through training in non-invasive prenatal testing (NIPT), high-resolution ultrasound, and standardized protocols for thalassemia and other prevalent monogenic conditions. Predictive medicine, including predictive testing for adult-onset disorders (e.g., hereditary cancers, cardiomyopathies), should be accompanied by robust informed consent and psychosocial support frameworks, tailored to Indonesia's cultural and legal landscape. Indonesia can draw lessons from other middle-income countries that have successfully scaled genomic medicine. For example, Thailand has integrated thalassemia screening into national antenatal programs, achieving a 90% reduction in new severe cases through targeted carrier screening and prenatal diagnosis [64]. Similarly, Malaysia has established a national rare disease registry and implemented subsidized genetic testing for selected

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conditions, demonstrating the feasibility of public–private partnerships in resource-constrained settings [65]. These regional examples underscore the importance of phased implementation, starting with high-burden conditions, and aligning genomic services with existing public health infrastructure.

Box – Key priorities for Indonesia (2025–2030)

- Complete 400,000-genome reference dataset with ethnic stratification
- Establish 2–3 national organoid core facilities for rare disease modeling
- Integrate genetic counselors into ≥20 provincial JKN referral hospitals
- Implement NIPT and carrier screening for thalassemia in high-prevalence regions
- Mandate genetic data protection law aligned with international standards

Ethical, legal, and social considerations remain central, with the need for data privacy frameworks, equitable access policies, and regulatory oversight for genome-based interventions. Aligning these developments with Indonesia's universal health coverage will be critical to translate genomic advances into a broad public health impact [Figure 3].

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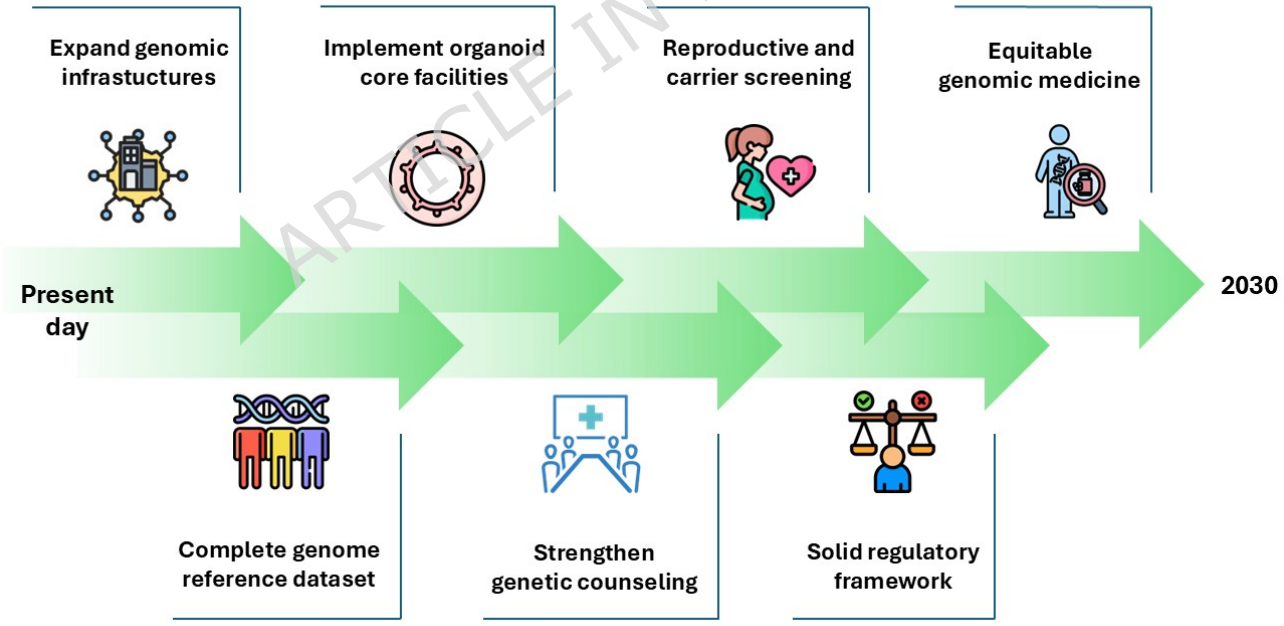


Figure 3. Roadmap outlining the key priorities for the development of medical genetics and genomic medicine in Indonesia: The roadmap summarizes the main strategic objectives identified in this review, including the expansion of genomic infrastructure, completion of a national genome reference dataset, development of translational research platforms, strengthening of genetic counselling services, implementation of reproductive genomic screening, establishment of robust ethical and regulatory frameworks, and promotion of equitable access to genomic medicine.

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10 Conclusion

Indonesia is undergoing a gradual yet significant transition toward integrating medical genetics and genomic medicine into its healthcare system. While the field is still in an early stage of development, recent national initiatives, particularly the Indonesian National Genome Project and the BGSi, reflect a growing commitment to precision medicine and population-specific genomic research. The country's extraordinary genetic diversity presents both a unique scientific opportunity and a critical imperative for developing tailored diagnostic, preventive, and therapeutic strategies.

Despite this progress, substantial challenges persist. Limited workforce capacity, uneven distribution of services, constrained research infrastructure, and high costs of advanced technologies continue to restrict access to genetic services. In particular, the implementation of precision oncology remains hindered by the high cost of genomic testing and limited reimbursement under the JKN–INA-CBG system, resulting in significant out-of-pocket expenditure and inequitable access. These barriers highlight the need for systemic reforms that align technological innovation with sustainable healthcare financing.

Looking forward, the successful integration of medical genetics into Indonesia's healthcare system will depend on a coordinated, multi-level strategy. This includes expanding genomic infrastructure, strengthening human resource capacity, developing population-specific genomic databases, and embedding genetic services into primary care and national insurance frameworks. In parallel, investments in translational research, such as functional disease models and multi-omics approaches, will be essential to bridge the gap between genomic discovery and clinical application.

Ultimately, Indonesia has the potential to emerge as a regional leader in genomic and precision medicine. Achieving this will require not only scientific advancement, but also policy alignment, equitable access, and the integration of genomics into public health systems. By addressing current structural and economic barriers, Indonesia can transform its rich genetic diversity into a strategic advantage, ensuring that the benefits of precision medicine are accessible, affordable, and impactful for its entire population.

Declarations

Ethics approval and consent to participate

Not applicable

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Availability of data and materials

Not applicable

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Authors' contributions

DC, EW, LDR, BW, VS, and GN conceptualized the project. DC, MB and GN wrote the original draft. JKVR contributed to the main manuscript text. All authors reviewed and edited the manuscripts.

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AI statement

No AI tools were used to generate text or figures.

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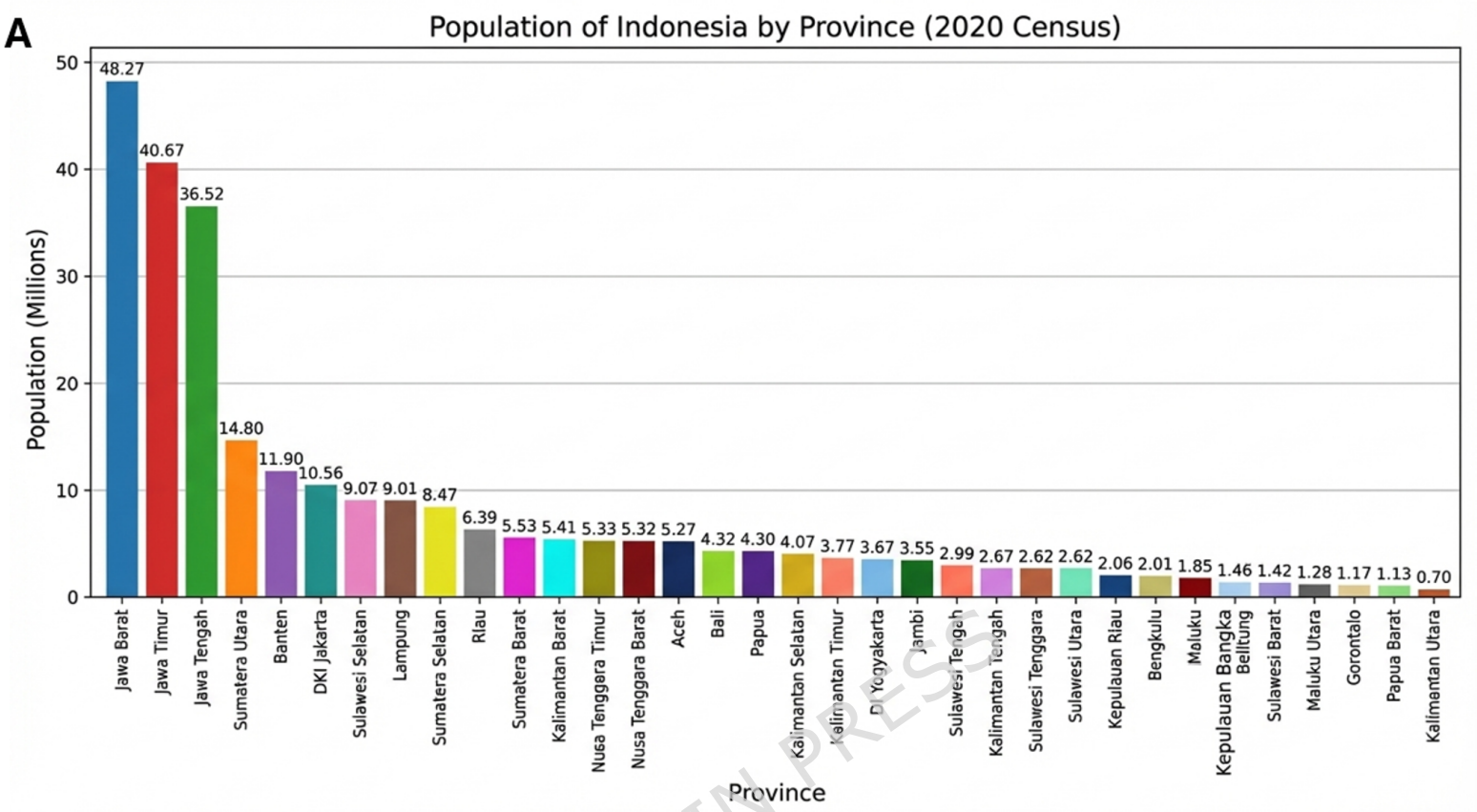
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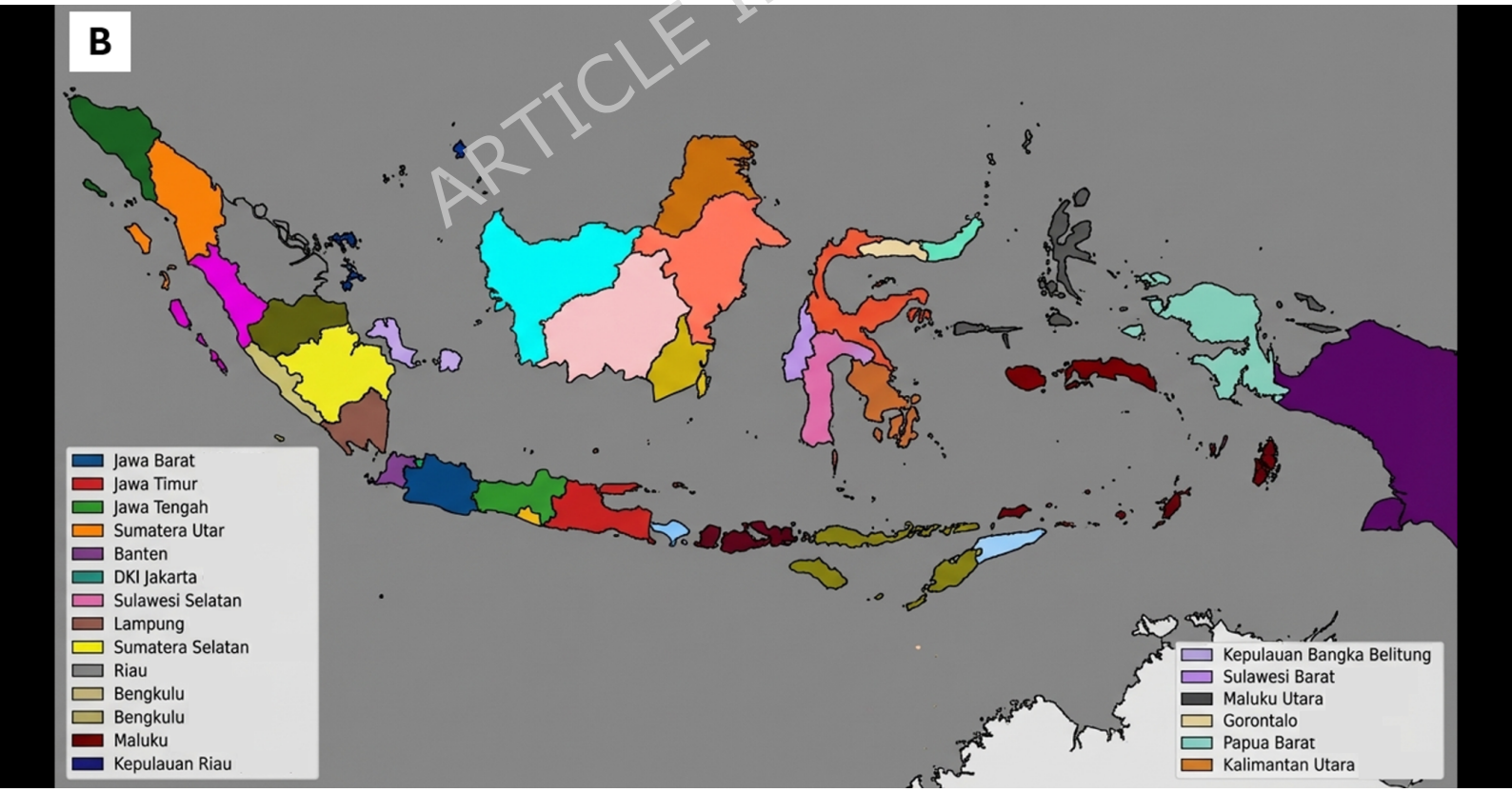
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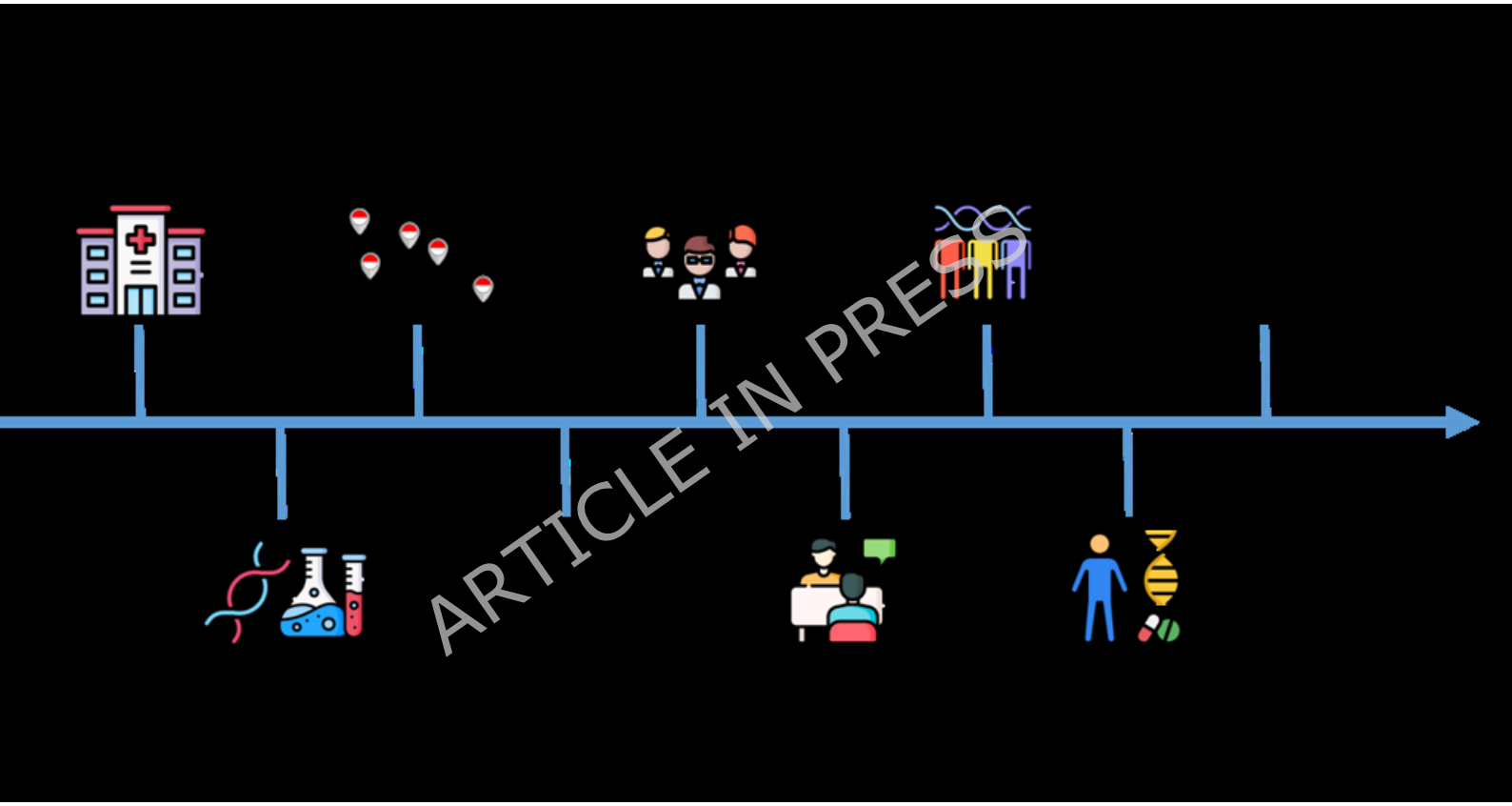
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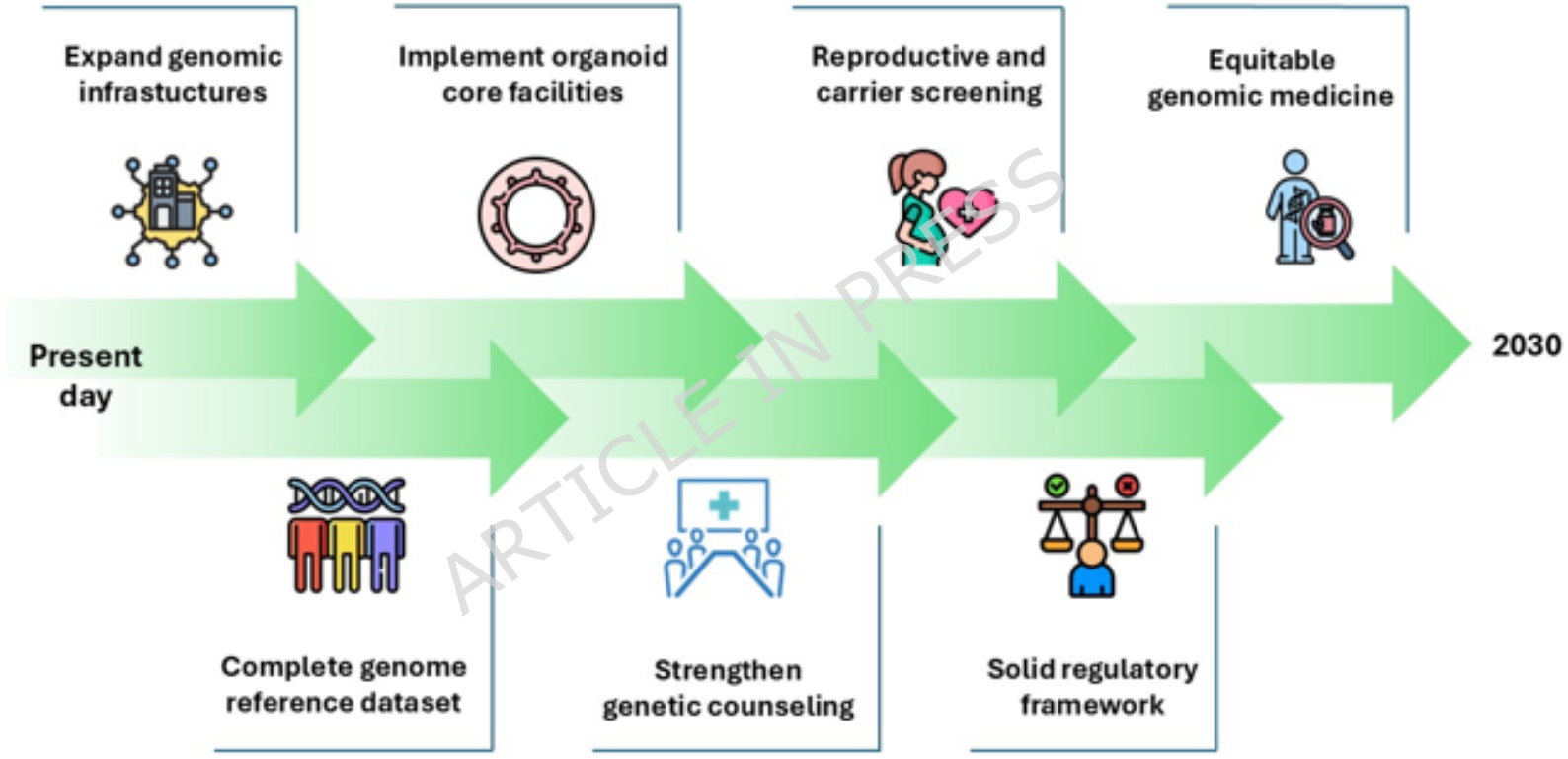


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Disease / Condition	Prevalence in Indonesia	Mode of Inheritance	Major Genetic Variants Reported	Clinica
β-Thalassemia	Carrier freq. 3–10%; ~2,500 affected births/year	Autosomal recessive	IVS-I-5 (G>C), CD26 (HbE), IVS-I-1, IVS-I-2, CD35, CD19; >12 variants in East Java alone	TDT, hepato deformities; mild to sever
α-Thalassemia	Carrier freq. 2.6–11%; varies by region/ethnicity	Autosomal recessive	Deletional (--SEA, -α3.7, -α4.2); non-deletional Hb Adana (Cd59, α2) up to 16% in some populations	Silent carrier fetalis (Hb B
Hemoglobin E (HbE)	Higher prevalence in western Indonesia and Austroasiatic-ancestry populations	Autosomal recessive (codominant)	HBB c.79G>A (Cd26, GAG>AAG); aberrant splicing in exon 1	Heterozygou homozygous HbE/β-thal: transfusion-d
G6PD Deficiency	0–20% (heterogeneous); majority of sites <5%; up to 25% in some eastern populations	X-linked recessive	Viangchan (p.V291M), Canton (p.R459L), Vanua Lava (p.L128P) in western Indonesia; distinct pattern in eastern populations	Acute hemol oxidative stre neonatal jaun in severe var
Tuberculosis (TB)	~354/100,000 population (high endemic burden)	Polygenic susceptibility (infectious disease)	VDR polymorphisms (FokI, ApaI, BsmI, TaqI); JAG1, TXNDC4, CCL17 (Indonesian GWAS cohort); CD209 variants	Pulmonary T extrapulmona show differe
Dengue Fever	Tens of thousands to >100,000 cases/year; all 4 serotypes circulate	Polygenic susceptibility (infectious disease)	MICB rs3132468 (DSS risk); PLCE1 rs3740360 (DHF in secondary infection); TLR and CD209 variants	Ranges from fever (DF), d (DHF), deng
Type 2 Diabetes Mellitus (T2DM)	~10.6% prevalence (2018 national survey); urban-rural disparity	Polygenic/multifactorial	TCF7L2, KCNJ11, KCNQ1, SLC30A8, CDKAL1; ancestry-adjusted PRS under development for Indonesian populations	Hyperglycem cardiovascula complication
Stroke & Cerebrovascular Disease	~16.1/1,000 population (Sleman District study); major contributor to disability	Polygenic/multifactorial	Hypertension- and lipid-associated loci; population-specific data limited; familial forms (CADASIL: NOTCH3; MELAS: mtDNA)	Ischemic and associated w dyslipidemia
Metabolic Syndrome	Prevalent in urban populations; linked to central obesity and dietary transition	Polygenic/multifactorial	FTO, PPARG, ADIPOQ variants; under-studied in Indonesian cohorts	Central obesi low HDL, hy hyperglycem
Depression & Anxiety	High prevalence (23.6% depression in national sample; Peltzer & Pengpid 2018); childhood adversity key risk factor	Polygenic/multifactorial	SLC6A4 (5-HTTLPR s-allele; higher frequency in East Asian populations); BDNF Val66Met; FKBP5 variants; population-specific data in Indonesia limited	Major depres anxiety disor associated w childhood ad

Table 1. Genetic and infectious diseases with documented genetic susceptibility reported in Indonesia: Summary of genetic and infectious diseases with documented or putative genetic susceptibility components reported in Indonesia. For each condition, estimated prevalence in the Indonesian population, mode of inheritance, major genetic variants identified in Indonesian or Southeast Asian cohorts, principal clinical manifestations, and current clinical management strategies are provided. Prevalence data are derived from national surveys and peer-reviewed literature [9 - 22]. For polygenic conditions, variants listed represent those most consistently reported in Asian or Indonesian cohorts; population-specific data for Indonesia remain limited for several entries. Abbreviations: TDT, transfusion-dependent thalassemia; HSCT, hematopoietic stem cell transplantation; DHF, dengue

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hemorrhagic fever; DSS, dengue shock syndrome; DOTS, directly observed treatment, short-course; PRS, polygenic risk score; VDR, vitamin D receptor.

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Domain	Then (Ariani et al., 2017)	Now (2026)
National genomics infrastructure	Limited to Eijkman Institute and a few university labs	BGSi established (2024); hub-and-spoke model; domestic NGS capacity
Genome sequencing capacity	Research-focused; no national program	National Genome Project: 10,000 genomes completed; target 400,000 by 2030
Genetic counselling	No formal training; limited awareness	Master's programs at Diponegoro & YARSI; ISGC established (2021)
Pharmacogenomics	Minimal clinical integration	Pilot programs in referral centres; population-specific pharmacogene data emerging
Precision oncology	Limited to research settings	*EGFR* testing in NSCLC; multigene panels for hereditary cancers; JKN reimbursement gaps remain
Carrier screening	Fragmented; no national policy	Regional thalassemia screening; NIPT pilot programs
Policy & regulation	No national genomic framework	BGSi formalized (2024); ethical and data protection frameworks under development
Public health integration	Minimal	JKN covers 98.45%; primary healthcare (PHC) as entry point for genomic services

Table 2. Major developments in medical genetics and genomic medicine in Indonesia over the past decade: Comparison between the landscape described by Ariani et al. (2017) and the current status (2026), highlighting progress in genomic infrastructure, clinical services, research capacity, national policies, and healthcare integration.

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Reference	Study population	Genes / genetic variants	Clinical relevance / application
Kothary et al. [46]	Indonesian and Singaporean populations representing major ethnic groups	*CYP2C9, CYP2C19, CYP2D6,* and *SLCO1B1*; 18 SNPs and 2 *CYP2D6* CNV markers	Pharmacogenomic testing and prediction of drug response and adverse drug reactions
Nugrahaningsih et al. [47]	Yogyakarta population, Indonesia. 190 individuals	Clinically relevant variants in *CYP2C9, CYP2C19, CYP2D6,* and *SLCO1B1*	Population-specific pharmacogenomic profiling and genotype-guided prescribing
Siswanto et al. [49]	~2,800 Indonesian individuals	Multiple common variants contributing to obesity susceptibility	Obesity risk prediction
BINUS University [50	Indonesian genetic samples and Asian population variant data	Multiple variants associated with hereditary cancers	Hereditary cancer risk screening

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Table 3. Pharmacogenomic and polygenic risk score studies relevant to the Indonesian population: Summary of studies investigating pharmacogenetic variation and polygenic risk scores in Indonesian populations, including study populations, genetic markers, potential clinical applications, and main findings**.**