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Definition and conceptual model of genetics literacy: a systematic literature review

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ABSTRACT

Genetic literacy is essential for promoting health and well-being in modern society. Although its importance is increasingly recognised, the definition and crucial dimension to construct a conceptual model are unclear, limiting the possibilities for measurement and comparison intervention. The study aims to review definitions and the conceptual models of genetics literacy and develop a new comprehensive definition and conceptual model based on the discovered dimensions that are relevant in the post-genomic era. We performed a systematic literature review using the Crossref, PubMed, and Scopus databases with Publish or Perish software. An automated content analysis was conducted to identify and develop conceptual model genetics literacy using NVivo 12 software. The review resulted in 10 definitions and 12 conceptual models. Automated content analysis showed that genetic literacy is defined as the ability of an individual to comprehend, use, correlate, assess, and propose genetic information to make arguments, reason, and decide on genetic issues in maintaining or improving the quality of personal and social well-being. Genetic literacy was conceptualised as a set of knowledge, a set of skills or interconnected. The conceptual model of genetics literacy covers two dimensions. i) Knowledge dimension: conceptual (nature of genetic material, transmission, genetic expression, genetic regulation, genetic determinism, genetic technology); sociocultural; epistemic. ii) Skills dimension: argumentation, informal reasoning, and decision-making skills. This definition and conceptual model can serve as a basis for developing interventions and measurements to support regulating, preventing, as well as promoting health and well-being.

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1. INTRODUCTION

Genetic literacy is increasingly required for future generations to participate in and respond to genetic issues in health, agriculture and fisheries to achieve well-being in the post-genomic era [1]. However, the definition of genetic literacy is still being debated, and no agreement has been reached, so it is crucial to develop a more comprehensive conceptual model in genetics literacy [2]. Genetic literacy, a term introduced in the 1994s [3], is increasingly essential for promoting health and well-being in modern society. It concerns people's capacity to fulfil the complex necessity of genetic issues to reach a healthy community in modern society [4]. Genetic literacy means placing one's well-being and effective participation of the genetic problems in social decisions, understanding which genetic principles influence it, and knowing how to address them [5]. Individuals with sufficient genetic literacy can take responsibility for their well-being, their families, and the community's well-being [6].

Keefe and Copeland [7] recognised that definitions and dimensions in literacy would continually develop based on relevant principles that follow age. It is essential to differentiate genetics literacy from literacy generally. The United Nations Education, Science and Culture Organization (UNESCO) pointed out that literate mainly meant terms' abilities to read and write. Since the mid-twentieth century, understandings of the term literacy have been constructed from the debate notion that it is literacy as i) an autonomous set of skills; ii) an applied, practised and situated; iii) a learning process; and also iv) a text [8]. Therefore, it is vital to know the appropriate definitions and conceptual models of genetic literacy in the post-genomic era that can serve as a basis for promoting genetic literacy in learning and assessment.

Genetic literacy is essential for future generations to participate in solving genetic-related issues so that they can train through a learning process [9]. However, the definition and dimension of genetic literacy need to be clarified to construct a conceptual model that will be useful for comparing learning and assessment [2]. To our knowledge, the identified dimensions still only accommodate the knowledge dimension. Genetic literacy is primarily defined as sufficient knowledge and appreciation of genetics principles to allow informed decision-making for personal well-being and effective participation in social decisions on genetic issues [5]. As a case in point, a deep understanding of genetic literacy will impact all aspects of life. The easy accessibility of information makes genetic content knowledge directly impact people's lives. The application of content in gene technology is increasingly expanding into the public sphere, increasing the importance of paying attention to genetic issues [10]. Moreover, depth knowledge of modern genetic content about the genome and its properties, such as genetic technology and genetic discrimination, is needed to respond to genetic issues [4]. For example, many advertising media spread hoax news related to the case of COVID-19, the issue of using genetically modified food and skin care products [9] Exposure to genetic information in the public sphere brings an individual need to ward off hoax news spread on social media, such as on Twitter [11], Facebook [12], and WhatsApp [13]. Furthermore, the goal of genetics literacy is extensive from individual to societal transformation by linking genetics literacy to sociocultural issues and economic growth so that skills dimensions to solve its issues are needed [14].

The extensive goals in genetics literacy bring individual needs to have skills in dealing with sociocultural issues in genetics. However, there still needs to be more consensus about what the dimensions represent in genetics literacy which is relevant for individuals in the twenty-first century. Individuals need skills to evaluate the veracity of claims on genetic issues and make informed decisions [15]. Shea *et al.* [2] argued that more than understanding genetic content that addresses genetic phenomena is needed, and individuals also need skills in genetic literacy to make appropriate decisions on genetic issues. In this case, genetic literacy is not only limited to the knowledge dimension, but also citizens must have skills dimension in genetics and be capable of using them. Thus, the two dimensions will discuss to define genetic literacy comprehensively in this study. The first dimension: is the using genetics knowledge to identify, explain [16]–[19], develop, promote, and evaluate reasons for genetics issues [20]–[22]. Then, we add to this definition by considering a second dimension: the role of a set of skills in influencing individuals' genetic literacy. Moreover, the dimensions of interest in assessing students' development of genetics literacy are increasing.

Several studies have developed various conceptual models in genetics literacy [23]–[25]. Nevertheless, similar progress lagged in constructing a new conceptual model that consists of knowledge and skills dimensions in genetics literacy that are relevant to today's society. Therefore, it is essential to investigate the main element in the knowledge and skills dimension of genetic literacy to achieve the goals of science education. Cebesoy and Tekkaya [26] stated that the Genetics Literacy Assessment Instrument, which contains the main element of the knowledge dimension that consists of the nature of the genetic material, transmission, genetics expression, genetics regulation, evolution, genetics and society, has yet to be able to measure the overall genetic literacy of biology students. Boerwinkel *et al.* [27] pointed out that genetic concepts of evolution and natural selection are irrelevant to genetic literacy. In line with the National Research Council [28] stated that many genetic concepts could be included to represent genetic literacy, asides from the concept of evolution. Furthermore, Cebesoy and Oztekin [29] revised the main element of knowledge in assessing genetic literacy by incorporating genetic determinism. Then, Aivelo and Uitto [1] suggested that educators should involve genetic technology in genetics literacy. Thus, the main element of the knowledge dimension in genetic literacy involves concepts which include: the nature of the genetic material, transmission, gene expression, gene regulation, genetic determinism, and genetic technology. Moreover, several studies also mention several skills in genetic literacy needed to make decisions on genetic issues, such as argumentation skills [22] informal reasoning skills [2] and decision-making skills [4]. Several studies showed these skills' importance in understanding genetics knowledge and genetics-related issues [30]. It is essential to construct a new conceptual model of genetics literacy because several studies show that broad, deep knowledge and skilful genetic literacy will impact all aspects of life, including health [31] well-being [16], and education [32].

Based on genetics literacy research and education policy, the dimensions of genetics literacy remain contradictory and attempt to operationalise the conceptual models vary widely. Moreover, it becomes clear that the need to develop a reconceptualisation of the definition and conceptual model of genetics literacy is relevant in modern genetics. To the best of our knowledge, only a few have specifically examined the definition and conceptual model of genetic literacy, especially in included skills dimensions that are important in the post-genomic era. Thus, this article aims to overcome this issue by offering a systematic review of existing definitions and dimensions to develop a conceptual model of genetics literacy by identifying the main element in each dimension of genetics literacy reported in the international literature. Furthermore, we develop a reconceptualisation of the definition and conceptual model to comprehensively capture genetics literacy based on evidence dimensions to achieve agreement about the definition and conceptual model of genetics literacy.

2. RESEARCH METHOD

To overcome the problem, we conducted research using a systematic literature review (SLR) procedure with Publish or Perish software. The SLR method can help summarise the latest knowledge on a particular topic systematically and transparently to answer research questions, especially about the definition and conceptual model of genetics literacy [33]–[35]. The stages of the SLR procedure adopt the framework of Arksey and O'Malley [36], which consists of five main steps, namely: i) identifying the research questions, ii) identifying relevant studies, iii) eligibility criteria, iv) study selection, v) collating, summarising, comparing, and reporting the results. The following is an explanation of each stage.

2.1. Identifying the research questions

The stage of identifying research questions was conducted to define the scope and develop a clear focus for the study. Three research questions were determined to guide the following SLR. i) how is genetics literacy defined? ii) what are the main elements in each dimension of genetics literacy? and iii) how can genetics literacy be conceptualised?

2.2. Identifying relevant studies

The stage of identifying relevant studies is to retrieve studies by determining the database and keywords used. A comprehensive literature search was conducted using the Crossref, PubMed, and Scopus databases. Furthermore, ten keywords were used to retrieve relevant literature, including concept, dimension, definition, framework, conceptual model, theory, qualitative, quantitative, skill, and competence, combined with genetics literacy and genetics competence.

2.3. Eligibility criteria

The stage of determining the eligibility criteria for selecting studies that will include in the review. Eligible studies were included that met the following inclusion criteria: i) articles published between 2000 to 2022; ii) articles published in English; iii) articles were solely connected to the definition or conceptualisation of genetic literacy and genetics competence or a combination of these issues.

2.4. Study selection

The article screening stage is based on research questions, relevant studies, and eligibility criteria. The article screening protocol refers to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework Gallagher *et al.* [37]. The study selection stages consist of several paths, namely: search, identification, and screening, and included are presented in Figure 1. Study selection begins with searching for articles using Publish or Perish software on Crossref, PubMed, and Scopus databases. The researchers discovered 235 during the initial search, so 92 articles were obtained from the Crossref database, 74 from the PubMed database, and 69 from the Scopus database. Then, 235 articles were entered into Mendeley software to separate duplicated articles so that 132 articles were retrieved. The researchers then filtered based on title and abstracts. Seventy-three articles met the criteria, which meant that 59 items were excluded. The researchers then filtered based on full-text articles assessed for eligibility. We retrieved 12 articles connected to the definition or conceptualisation of genetic literacy and genetics competence, which meant that 61 items were excluded. Furthermore, 12 articles were analysed by automated content analysis (ACA).

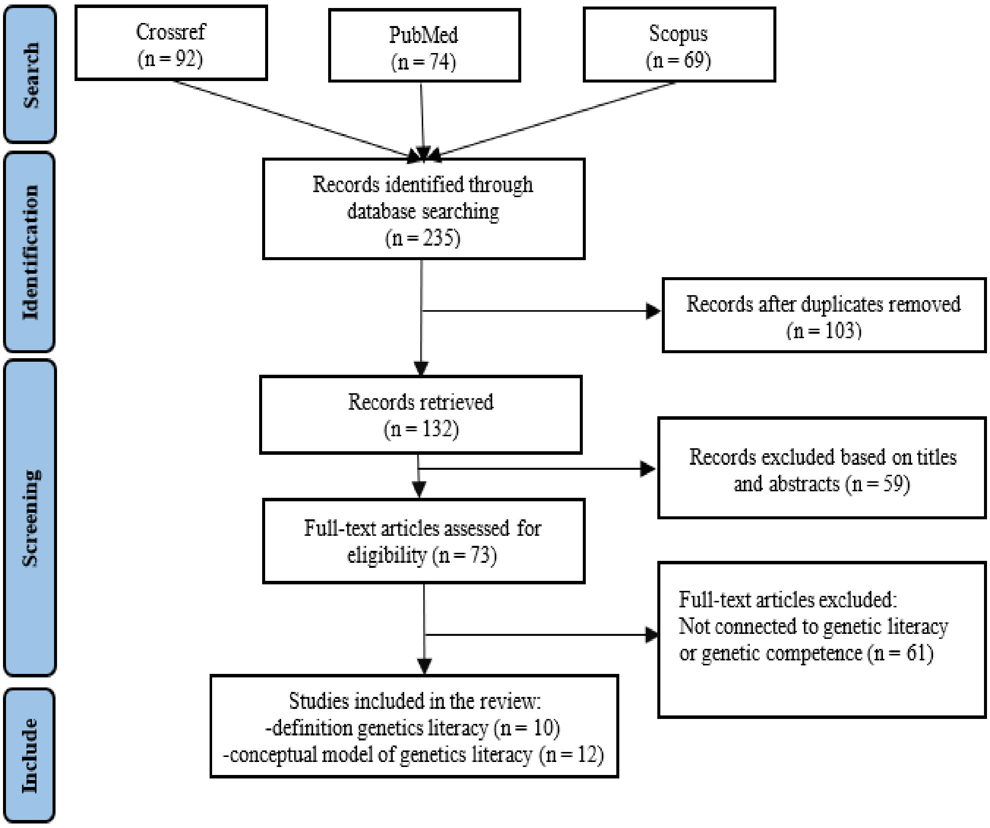

Figure 1. Study selection stages flow

2.5. Collating, summarising, comparing, and reporting the results

The reporting stage is carried out by analysis of ACA using NVivo 12 to analyse component genetic literacy from eligible literature [38]. Data analysis was carried out through four processes referring to Trilling and Jonkman [39]. i) coded and condensed by reviewing the definition and concept from the eligible article. ii) summarised each article includes the following components: author and year of publication, subjects, core concept, skills, item type, core information, and additional information. iii) the definitions were coded and condensed by two research teams working independently. iv) the process of comparing essential elements and developing a conceptual model of genetic literacy.

3. RESULTS AND DISCUSSION

Various kinds of literature have diverse definitions and conceptual models of genetic literacy. However, there has yet to be an agreement on the relevant definition and conceptual model of genetic literacy, especially in the post-genomic era. Therefore, we performed an SLR to address this issue, and 235 eligible publications were retrieved from the three databases. Furthermore, the study selection process resulted in 22 relevant publications. The study selection process resulted in 10 publications explicitly addressing the definition of genetic literacy and 12 discussing the conceptual model of genetics literacy for our systematic review. Furthermore, the research team used ACA techniques by comparing and contrasting to produce a comprehensive new definition and conceptual model to construct dimensions of genetic literacy by considering the context and development of genetics disciplines in today's society. Based on ACA, we have developed: i) a new definition of genetic literacy, ii) a new conceptual model of the knowledge dimension in genetic literacy, and iii) a new conceptual model of the skills dimension in genetic literacy, which are explained as follows.

3.1. Definitions of genetics literacy

Ten explicit definitions could be derived from the 12 publications focusing specifically on definitions of genetics literacy Table 1 of these definitions, the reports of Andrews *et al.* [3] and McInerney [5] are cited most frequently in the literature that emphasises genetic literacy on the knowledge dimension. Andrews *et al.* [3] and McInerney [5] defined genetic literacy as sufficient knowledge of genetic principles to make informed decisions on genetic issues to support personal and social well-being. Jennings [40] also stated that genetics literacy is a part of genetic-literate citizenship, including participation in societal and individual decision-making, especially in genetic-related services. Then, Duncan *et al.* [17] explained that genetic literacy is an individual's ability to understand, use, and respond to genetic phenomena and technologies related to everyday life.

Table 1. Definitions of genetics literacy

References	Description of the definition of genetics literacy
[3]	"An informed decision maker by providing genetics knowledge to increase options, help people make informed choices, and promote an appreciation and acceptance of differences"
[5]	"Sufficient knowledge and appreciation of genetics principles to allow informed decision-making for personal well-being and effective participation in social decisions on genetic issues"
[40]	"A part of genetic-literate citizenship which includes both participation in societal deliberation on genetic-related issues and personal decision-making on the use of genetic-related services"
[17]	"The ability to comprehend, use, or respond to information about genetic phenomena and technologies that an individual may encounter in everyday life situations"
[10]	"The ability to use genetic content (knowledge about deoxyribonucleic acid (DNA), genes, chromosomes, patterns of inheritance) and genetic issues (the ethical questions related to genetic testing, genetic engineering and genetically modified organisms)"
[2]	"The capacity to use genetic content knowledge, argumentation quality, and the role of situational features in reasoning"
[27]	"Conceptual (knowledge of genetic concepts); sociocultural (knowledge of how applications of genetic technologies are used and influence in societal activities; epistemic (knowledge needed to interpret genetic information and how to use these in argument and decision-making)"
[4]	"Understanding science content knowledge and practices and use it in decision-making related to SSIs and their interconnections"
[29]	"Understanding of genetics concepts and the skills needed to participate in informed decision-making situations arising from genetics technologies"
[9]	"Raising knowledge and enabling people to express informed opinions and engage in discussions and debates regarding applications of genetic knowledge"

Moreover, Kampourakis *et al.* [10] assumed that genetics literacy has two distinct components, knowledge about genetics and ethical questions related to genetic issues. More recently, Boerwinkel *et al.* [27] attempted to determine citizens' genetic knowledge to decide on genetic-related issues: conceptual, sociocultural, and epistemic. Conceptual is knowledge of genetic concepts; sociocultural is knowledge of how applications of genetic technologies; and epistemic is knowledge of how to use information in argument and decision-making. However, several discussions in the recent literature about genetics literacy highlighted the importance of skills in dimensions of genetic literacy.

In recent years, advances in genetic research have led to the need to reconceptualise the dimensions of genetic literacy. Recent publications about genetics literacy promote essential skills so that the dimensions of genetics literacy are not only about knowledge but also skills. Shea *et al.* [2] respond to this fact by making a tri-part model of genetic literacy, which consists of knowledge, the quality of argumentation, and the role of reasoning skills. More recently, Stern and Kampourakis [4] attempted to clarify the definition of genetic literacy as the interconnection between understanding genetic content and its application in decision-making skills on socio-scientific issues. The broader view is presented in the report proposed by Cebesoy and Oztekin [29], who stated that genetics literacy requires sufficient knowledge of genetic concepts such as the nature of the genetic material, inheritance, gene expression and regulation and skills needed to participate in decision-making based on information from genetic technology. Chapman *et al.* [9] underscored that genetics literacy is not only about increasing knowledge but also being able to express opinions and engage in discussions on the application of genetic knowledge.

Furthermore, the research team identified the essence of ten definitions of genetics literacy. Then, we carefully examined, discussed, and summarised the results of the identification of genetic literacy. Finally, selected terms and ideas are combined to produce a comprehensive new definition.

> *Genetic literacy is related to knowledge of genetic principles and individual competence to comprehend, use, correlate, assess, and propose genetic information to make arguments, reason, and decide on genetic issues in maintaining or improving the quality of personal and social well-being.*

This new definition accommodates the dimensions of knowledge and skills relevant to literate genetic needs to raise the quality of personal and social well-being in daily life.

3.2. Dimensions of genetics literacy

Over the past two decades, scholars have attempted to clarify the definition and dimensions of genetic literacy. However, the dimension of genetics literacy needs to be clearly defined in the research literature, causing unclear specific elements of its dimensions. From this overview, two issues become defined. Firstly, when reviewing various publications, there are two kinds of publications of genetic literacy: i) publications of genetic literacy that emphasise a knowledge dimension and ii) publications of genetic literacy that emphasise knowledge and skills dimensions. Secondly, an overview of all models from the eligible literature was carried out, and conceptual models were compared according to dimensions. As a result, a new conceptual model was designed to capture the most comprehensive core dimensions related to genetic literacy.

3.2.1. Knowledge dimension in genetic literacy

The different instruments have reflected the unclear definition of genetic literacy in recent years, so knowing the main elements in the knowledge dimension is needed. Boerwinkel *et al.* [27] stated that knowledge of genetics is required for decision-making on genetic-related issues consisting of conceptual, sociocultural, and epistemic knowledge. However, the developed instruments still accommodate conceptual concepts, and there is still a debate about the main elements of the knowledge dimension of genetics literacy. Thus, the identification of the main element in the knowledge dimension from genetic literacy instruments is needed, as shown in Table 2.

Table 2. Conceptual models of knowledge in genetics literacy

Author(s)	Subjects	Concept	Item type	Core information	Additional information
[23]	Higher Secondary	a. Genetics (classical), b. genetics (molecular), c. cell biology, reproduction.	Nine items questionnaire	The instrument can diagnose that classical and molecular genetics taught at different levels are often unrelated.	The instrument assesses conceptual understanding of classical and molecular genetics
[24]	Science majors undergraduate	a. Evolution, b. ecology, upper-level genetics.	30 items multiple-choice	The instrument was developed from the problematic concepts of molecular biology and evolution.	a. The tool involves general biology core concepts. b. The validity and reliability of the tool are not informed.
[25]	Majors and non-science majors in undergraduate	a. Inheritance of various traits, b. transmission, and genetic diseases.	25 items multiple-choice	a. The instrument measures complete validity and reliability. The tool examines common misconceptions in genetics.	a. The core concepts in the tool still focus on the ideas of some common genetic misconceptions.
[16]	Non-science majors undergraduate	a. Nature of the genetic material, b. transmission, c. gene expression, d. gene regulation, e. evolution, genetics and society.	31 items multiple-choice	a. The instrument measures complete validity and reliability. The instrument measures psychometric properties.	a. The instrument does not have enough to describe teachers' genetic literacy level. The core concepts in the tool are designed for undergraduate non-science majors.
[26]	Pre-service science teacher	a. Nature of the genetic material, b. transmission, c. gene expression, d. gene regulation, e. evolution, genetics and society.	39 items multiple-choice	The instrument introduces the importance of understanding and reasoning on ethical, legal, and social issues, patient rights, and genetics technology.	a. The core concept of the instrument still involves the idea of evolution. Validity and reliability were analysed by classic test theory.
[41]	Undergraduate students of Biology Education and Biology study programs	a. Nature of the genetic material, b. transmission, c. gene expression, d. gene regulation, e. evolution, genetics and society.	13 items questionnaire	a. The instrument measures complete validity and reliability. b. The tool measures psychometric properties. The questionnaire focuses on the genetic issue of COVID-19.	The core concept of the instrument still involves the idea of evolution.

Chattopadhyay [23] identified four core concepts to measure genetics knowledge through a questionnaire, namely: genetics (classical), genetics (molecular), cell biology, and reproduction. The questionnaire can diagnose the importance of integrating genetic knowledge with other scientific disciplines. However, these instruments assess part of genetic concepts. Then, Garvin-Doxas and Klymkowsky [24] attempted to develop a biology concept inventory (BCI) with 30 multiple-choice questions that involved problematic concepts of molecular biology and evolution. However, BCI measures three core concepts of biology in general: evolution, ecology, and upper-level genetics. Finally, Smith *et al.* [25] developed a genetics concept assessment (GCA), which examines common genetic misconceptions: inheritance of various traits, transmission, and congenital disease.

Nevertheless, the core concepts in the GCA focus on some common genetic misconceptions. For example, Bowling *et al.* [16] have attempted to develop a genetic literacy assessment instrument (GLAI) with 31 multiple-choice items for non-science primary students so that it is not correctly relevant when used to test the genetic literacy of science major students. The core concept in GLAI includes six main ideas: nature of the genetic material, transmission, gene expression, gene regulation, evolution, and genetics and society, referred to by Hott [42]. On the contrary, Cebesoy and Tekkaya [26] modified GLAI items with 39 multiple-choice items, which are more relevant to genetic concepts. The test instrument of Cebesoy and Tekkaya [26] also contains the core concepts of genetics referred to by Hott [42]. Then, Fauzi *et al.* [41] attempted to develop a 13-item questionnaire. The questionnaire contains the core concepts of genetics, also referred to by Hott [42]. Thus, several instruments in genetics still emphasise conceptual knowledge and have lagged in comprehensively representing what core concepts to represent genetics literacy.

Several instruments of genetics literacy mainly contain the core concepts of genetic material, transmission, gene expression, gene regulation, evolution, and genetics and society. On the one side, Cebesoy and Tekkaya [26] pointed out that those core concepts do not adequately describe pre-service teachers' genetic literacy level. In addition, Boerwinkel *et al.* [27] argued that evolution and natural selection are not included in genetic literacy because many other core biological ideas are also related to the concept of genetics, and their inclusion would result in an expansion of the description of gene literacy throughout biology. This distinction is in line with the National Research Councils's framework for K-12 science education [28], which lists four core ideas that represent essential areas of inquiry in the life sciences, in which heredity and evolution emerge as two separate core ideas. Furthermore, Cebesoy and Oztekin [29] assumed the importance of human rights in genetic determinism concepts. On the other side, Aivelo and Uitto [1] also suggested that students in the post-genomic era should understand genetic technology.

In conclusion, genetic literacy instruments have core concepts in various conceptual models of the knowledge dimension. However, it is necessary to reduce and add core concepts due to variations in conceptual models to get a knowledge dimension relevant to the twenty-first century. Thus, the core concepts to construct new conceptual models of knowledge dimension in genetic literacy found in this study are: i) the nature of genetic material, ii) transmission, iii) genetic expression, iv) genetic regulation, v) genetic determinism, and vi) genetic technology. We decided to build the six core concepts in genetic literacy through a process of comparison and contrast from six relevant pieces of literature from SLR and consider the context of the development of the discipline of genetics in today's society. Our analysis in deciding on the six core concepts in genetic literacy is based on the principle that the discipline of genetics is composed of fundamental concepts that follow the nature of science. Science has a dynamic nature which means that scientific understanding will continue to change along with further research, whose primary purpose is to strengthen concepts. Thus, core concepts such as i) the nature of genetic material and ii) transmission have been expanded and improved over a century. On the other hand, other core concepts, such as iii) genetic expression and iv) genetic regulation, have been recognised for decades as important concepts. Furthermore, research in the last 10-20 years showed that technological advances had enabled researchers to explain the core concepts of v) genetic determinism and vi) genetic technology.

3.2.2. Skills dimension in genetic literacy

UNESCO pointed out that one of the meanings of literacy is a set of skills. However, there is still no consensus about what skills are relevant to genetics literacy. As previously noted, the development of the genetic literacy assessment has lagged in comprehensively measuring the skills component, as described by Stern and Kampourakis [4]. Moreover, researchers have not agreed on the construction of skills in genetic literacy needed to understand genetics-related issues [15]. Thus, the identification of skills dimensions to find skills that encompass genetics literacy is shown in Table 3.

Various instruments have been developed by integrating the components of genetic concepts and skills relevant to genetic literacy. For example, Zohar and Nemet [22] measure students' argumentation skills on genetic counselling, information about genetic traits, gene therapy, and genetic cloning. The instrument assesses the validity of the content but does not yet inform the validity of the construct. Furthermore, Sadler and Zeidler [43] measured students' informal reasoning skills on genetic disease, cloning, and engineering concepts. Sadler and Zeidler [43] proved that students with a better understanding of genetics would involve content knowledge in the informal reasoning process in responding to genetic issues. Sadler [21] also conducted interviews to see the decision-making skills of students at the undergraduate level.

Table 3. Conceptual models of skills in genetics literacy

Author(s)	Subjects	Core concept	Skills	Item type	Core information	Additional information
[22]	Junior high school	a. Genetic counselling, b. information genetic traits, c. gene therapy, genetic cloning.	Argumentation skills	20 items multiple-choice	Instruments can promote the importance of modern genetic technology.	The instrument assesses the validity of the content but does not yet inform the validity of the construct.
[43]	Undergraduate Students	a. Huntington's disease, b. nearsightedness gene therapy, c. intelligence gene therapy, d. reproductive cloning, e. deceased child cloning, f. therapeutic cloning, genetic engineering.	Informal reasoning skills	23 items multiple-choice	The instrument proves the signification of conceptual knowledge in informal reasoning.	The validity and reliability of the tool are not informed.
[21]	Non-science majors and biology majors	a. Huntington's disease, b. nearsightedness gene therapy, c. intelligence gene therapy, d. reproductive cloning, e. deceased child cloning, f. therapeutic cloning, genetic engineering.	Decision-making skills	Interview	The instrument explores the evolution concept effect on reasoning in genetic engineering.	The validity and reliability of the instrument are not informed.
[44]	Pre-university students, biology teachers	Genetic testing.	Moral reasoning	Interview	The instrument introduces the importance of intuition and emotion in reasoning genetic issues.	The instrument focuses on a single concept of genetic testing. Instrument validity is not informed.
[29]	Science teachers	a. General attitudes, b. use of genetic information, c. abortion, d. pre-implantation genetic diagnosis, gene therapy,	Informed decision-making skills	50 items-questionnaire	The instrument introduces the attitude aspect of genetics.	Validity and reliability are measured comprehensively.
[1]	Secondary school	a. Self-concept in genetics b. Linking genetics c. Experiencing the utility of genetics d. Attitude towards gene technology Belief in genetic determinism	Informed decision-making skills	25 items-questionnaire	The instrument incorporates the concepts of gene technology and determinism.	Instrument reliability is not disclosed.

Several years later, Van der Zande *et al.* [44] introduced the importance of moral reasoning skills in understanding the concept of genetic testing to maintain health. Van der Zande *et al.* [44] developed an instrument for measuring moral reasoning and showed that intuition and emotion play a role in an individual's reason when faced with a dilemma. The instrument contains a single concept of genetic testing. Furthermore, Cebesoy and Oztekin [29] pointed out that the instrument Bowling *et al.* [16] did not adequately describe pre-service teachers' genetic literacy level. Cebesoy and Oztekin [29] consider genetic attitudes essential because experienced teachers who consider themselves knowledgeable were found to lack genetic literacy and have negative attitudes towards gene therapy applications. Furthermore, Aivelo and Uitto [1] suggest that future generations should have decision-making skills in responding to genetic technology. Based on this description, the transformation of the scope of skills in measuring genetic literacy is needed to respond to genetic issues.

Several studies mention several skills in genetic literacy that are needed to make decisions on genetic issues, such as argumentation skills [22], informal reasoning skills [2] and decision-making skills [4]. Integrating these three skills into one measurable construction is needed to evaluate biology students' mastery of skills in genetics literacy. Genetic literacy requires a good understanding of genetic concepts and informed decision-making skills to participate in decision-making situations arising from genetic technology [29]. Furthermore, Aivelo and Uitto [1] suggested that educators teach informed decision-making skills so that they can participate in responding to opportunities, threats, and ethical issues related to gene technology and genetic determinism so that they can make the right decisions.

The complex nature of the problem of genetic issues drives the need for students to have the skills to be able to make decisions on genetic issues. Therefore, students need to be trained in skills relevant to genetic literacy, such as involving argumentation skills, applying informal reasoning skills, and integrating various perspectives in developing decision-making strategies. According to the dual process theory, individuals will involve in decision-making from two different cognitive systems, namely the intuitive system (implicit) and the analytical system (explicit) [45] Intuitive systems are more influenced by emotions connected to previous experiences but different analytical systems [46]. According to Fang *et al.* [47], students can use analytical techniques to perform logical thinking and decision-making skills. Analytical decision-making skills integrate argumentation, informal reasoning, and decision-making skills.

Three essential skills in genetic literacy are needed to respond to genetic-related issues. We decided on the most critical and relevant skills in genetic literacy by comparing and contrasting the six literature results from SLR. Thus, the new conceptual models of skills dimension in genetic literacy found in this study are i) argumentation skills, ii) informal reasoning skills, and iii) decision-making skills. Currently, the application of genetic technology is showing more progress and developing widely in society which triggers the emergence of genetic-related issues. As part of society, students need to be able to apply core genetic concepts to contribute and participate in responding to genetic-related issues. Students need thinking skills in applying core genetic concepts to support thinking and reasoning. i) Argumentation skills can train students to make claims with evidence and reasons through justification quality and evidence credibility. ii) Informal reasoning skills can improve students to solve controversial problems with many solutions through interdisciplinary thinking, decision-making mode, and setting criteria and priorities. iii) Decision-making skills are needed for students to make decisions based on ethical and logical considerations through social interactions meta-decision. These three skills are expected to be learned in genetics learning and used to assess genetic literacy. Educators and researchers can teach these skills by raising genetics-related issues in the post-genomic era.

3.3. Conceptual model of genetics literacy

In this study, we synthesise the results from 22 studies and find that genetic literacy is generally viewed as a distinct typology representing levels of knowledge and skills. These typologies progressively support greater autonomy and personal empowerment to make health-related decisions and participate in genetic issues to achieve social well-being [1], [6]. Genetic literacy began as a concept related to using genetic knowledge to make decisions that support individual and social well-being [3], [5]. Thus, it is not surprising that all the included studies examined the concept of genetic literacy from a knowledge dimension [3], [5], [16], [23]–[26], [48]. A genetic literate is considered an individual with sufficient genetic knowledge to process and use genetic information to make decisions, which is the study's primary concern. Based on ACA showed the need to develop: i) a new definition of genetic literacy, ii) a new conceptual model of the knowledge dimension in genetic literacy, and iii) a new conceptual model of the skills dimension in genetic literacy, which is explained as follows.

The first is a new definition of genetic literacy. The conceptual extension of genetic literacy results from empirical questions about the meaning of gene literacy in life. Several studies explore the importance of genetic literacy from the perspective of different populations. The differences in theoretical analysis in the early stages provide empirical evidence for changing the concept of genetic literacy. The original widely used definition of genetic literacy emphasises mastery of the knowledge dimension. Thus, we propose a new definition of gene literacy by combining all the relevant themes identified from the existing studies.

> *"Genetic literacy is related to knowledge of genetic principles and individual competence to comprehend, use, correlate, assess, and propose genetic information to make arguments, reason, and decide on genetic issues in maintaining or improving the quality of personal and social well-being."*

This definition highlights the diversity of needs of different individuals and the importance of interactions between individuals, health care providers, and the health promotion system to maintain health [32]. The new definition of genetics literacy is conceptualised as a set of knowledge, skills, or interconnected. The second is a new conceptual model of the knowledge dimension in genetics literacy. Genetic literacy is generally defined as an individual's ability to use genetic knowledge that consists of the nature of the genetic material, transmission, gene expression, gene regulation, evolution, and genetics and society. Nevertheless, a concept needs to be reduced and added due to variations in views to get relevant genetics concepts for citizens in the twenty-first century. For example, Boerwinkel *et al.* [27] argued that genetic literacy does not include evolution and natural selection. Thus, the core concepts in genetic literacy consist of the nature of genetic material, transmission, genetic expression, genetic regulation, genetic determinism, and genetic technology [1], [23], [25], [27], [29], [48]. We add genetic determinism and genetic technology because it is a fundamental concept that has significantly contributed to responding to genetic issues in recent years [23], [25], [29].

The new core concepts in the new conceptual model of the knowledge dimension in genetics literacy consist of: i) the nature of the genetic material refers to the study of genetic material in all living things containing genetic information that allows for genetic variation [49]. ii) transmission relates to the study of patterns of inheritance [50]. iii) genetic expression studies decoding dna's information to its functional forms [51]. iv) genetic regulation refers to the study of how cells control the specific amount of gene product produced [52]. v) genetic determinism relates to the study of the understanding of genetics, mainly focusing on a one-to-one relationship between genes, proteins, functions, and traits [53]. vi) genetic technology refers to the study of the use of molecular biology techniques to modify dna sequence(s) by using a variety of approaches [54].

The third is a new conceptual model of the skills dimension in genetic literacy. The concept of genetic literacy has evolved over the last few decades. Skills in genetic literacy have a significant role in shaping the way of thinking of individuals in obtaining and using information related to genetic issues [2], [21], [47], [55]. Then, there are doubts about the usefulness of information and knowledge because highly knowledgeable people may not be able to apply the acquired genetic knowledge. As a result, some researchers recommend adding skills in genetic literacy [1], [2], [48], [56]. For example, during the COVID-19 pandemic, a lot of gene information makes an individual need to ward off hoax news on social media [57]. Thus, individuals need situational skill features to evaluate the veracity of claims on genetic issues and make informed decisions [41]. The literature also indicates that the evaluation of genetic information has not been included in previous systematic reviews. Information evaluation is critical in the information age, where individuals receive much information. In such circumstances, people must be able to identify, explain, develop, promote, and evaluate various genetic details to demonstrate the right decisions [10].

The new conceptual model of the skills dimension in genetics literacy consists of: i) Argumentation skills refer to justifying knowledge claims with evidence and reasons [55]. Argumentation skills relevant to genetics literacy include: (a) justification quality relates to making arguments against social issues involving the latest research results (b) evidence credibility refers to proving the credibility of genetic information. ii) Informal reasoning skills related to cognitive and emotional processes contribute to solving controversial issues with many solutions appropriate to socio-scientific issues [58]. Informal reasoning skills that are relevant to genetics literacy, including: (a) interdisciplinary thinking refers to identifying genetic issues and concepts from various perspectives, (b) decision-making mode relates to deciding solutions based on relevant genetic information, (c) criteria setting and priority refers to analysing the role and consequences of making genetically engineered products. iii) Decision-making skills relate to decision-making processes involving more than one reasoning strategy, at least in practice, intuitive and analytical approaches [59]. Decision-making skills relevant to genetics literacy include: (a) social interactions refer to evaluating genetic information based on scientific ethics, (b) meta-decision relates to choosing solutions based on logical considerations.

All in all, the main goal of gene literacy education is to maintain health and achieve prosperity by using genetic information, knowledge, and skills [4]. The new conceptual model of genetics literacy that relevant in today's society showed covers two dimensions. i) knowledge dimension: conceptual (nature of genetic material, transmission, genetic expression, genetic regulation, genetic determinism, genetic technology); sociocultural; epistemic. ii) skills dimension: argumentation, informal reasoning, and decision-making skills. This study makes a significant contribution to the conceptualisation of genetic literacy. A system-wide view can help people better understand the role of genetic literacy and what needs to be done to improve genetic literacy [1], [9], [29], [58].

3.4. Limitations

Several criteria limit this research. First, the quality of publications is not assessed because some cited publications are considered very influential in reconceptualising genetic literacy. Second, the included studies were limited to studies published in English. Third, this study focuses on the literature published in the last 22 years. In addition, this study believes that the topic of genetic literacy will continue to evolve. The literacy proposed through the first systematic definition in this study is a step. Further studies are needed to define better and conceptualise genetic literacy.

3.5. Implications and recommendations for future research

Studies on genetic literacy show that genetic-related issues, which at least cover the fields of agriculture, health, and society, are essential to be taught in the classroom. However, several researchers have made different conceptual models of genetic literacy. Thus, a reconceptualisation of the definition and conceptual model of genetic literacy that comprehensively covers all elements is needed. Further research can develop learning interventions or measurement tools relevant to this study's conceptual model. Policymakers also need to make the basis of this research to support the improvement of genetic literacy in the learning process.

4. CONCLUSION

Genetic literacy has generally been conceptualised as a set of knowledge and skills. We propose to define genetic literacy as knowledge of genetic principles and individual competence to comprehend, use, correlate, assess, and promote genetic information to make arguments, reason, and decide on genetic issues in maintaining or improving the quality of personal and social well-being. Specifically, the definition includes the essence of the two dimensions identified from the literature review: knowledge and skills. Knowledge dimension in genetic literacy refers to conceptual, sociocultural, and epistemic. Conceptual knowledge consists of: i) the nature of genetic material, ii) transmission, iii) genetic expression, iv) genetic regulation, v) genetic determinism, and vi) genetic technology. Skills dimension in genetic literacy relate to: i) argumentation skills refer to justification quality and evidence credibility, ii) informal reasoning skills relate to interdisciplinary thinking, decision-making mode, and criteria setting and priority; and iii) decision-making skills refer to social interactions and meta-decision. Based on this principle, this model can serve as a basis for developing interventions and measurement tools. As currently available tools to measure genetic literacy do not capture all aspects of the concept as discussed in the literature, there is a need to develop new tools for assessing genetic literacy that reflect the definition of gene literacy and its conceptual model. Thus, further research can create an instrument to measure comprehensive genetic literacy. The instrument is expected to reflect the situation in the field and can be applied to social research. The instrument is expected to be the basis for planning appropriate genetic learning interventions so that it can contribute to understanding genetic literacy.

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