Using Visualization Models to Speculate on New Platforms for Additive Manufacturing Expansion

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***Abstract*—As Additive Manufacturing (AM) continues to grow, what constitutes its definition is also fragmenting and becoming blurred. The blurring of definitions may lead to slow understanding of AM technology, particularly in developing nations. To address this problem, the study proposes an expanded definition of AM based on the American Society for Testing and Materials (ASTM) standard AM definition. To examine the possible applicability of the expanded AM definition framework, the study considers conventional manufacturing processes and selected AM 'outliers' that are not traditionally classified as AM under the ASTM definition, yet exhibit specific similar attributes, to appraise the framework. The relationship between AM outliers are visualized to highlight possible future forms of additive manufacturing. In conclusion, the study argues that these visualization models may expand the definition of AM for new areas of applications, specifically in developing countries.**

***Index Terms*—Additive manufacturing definitions, parallel coordinates, relationship mapping, speculative thinking**

I. Introduction

The expansion of AM technology is influencing the emergence of new business models and will continue to do so in the future [1]-[3]. Though AM is contributing value to businesses in industrialized countries, it remains less known in developing countries [4], [5]. Some factors which may lead to the low uptake of AM could be attributed to lack of understanding of AM technology. AM as a new disruptor of making products [5], means that its definition framework and how people interpret it becomes a significant issue.

In [6], ASTM standard defines AM as '*the process of joining materials to make objects from three-dimensional model data, usually layer upon layer as opposed to the subtractive manufacturing processes.*' ASTM classify AM processes into seven categories which are *1. VAT Polymerization, 2. Material jetting, 3. Binder jetting, 4. Material extrusion, 5. Powder bed fusion, 6. Sheet lamination, 7. Directed energy deposition* [7]. Majority of AM researchers focus on materials and engineering aspects, whereas less research is focused on how the technology evolves regarding its definitions and process [8]. In [8], Killi posits that AM research is limited in terms of software tools to develop 3D form, which if given more attention may lead to the development of AM. The original understanding of AM as a tooling and prototyping technique seems to be limiting its evolution away from these traditions [2], [7], [9]. However, [4] emphasize that AM encompasses more than just confining to building objects in layers using computers and printers. In [10], the concept of morphogenesis is suggested as a value generator for users in making objects, for example hylomorphic 3D printing. The latter is one way of breaking away from the traditions of AM into new spaces of AM innovation by interacting with materials. Other exotic AM examples can be seen in [2], [20].

This paper argues that the expanded definition of AM may lead to the development of new understanding and techniques around digital manufacturing and critically – these new understandings may help to identify opportunities for novel applications of AM in industrialized and developing countries. The ASTM definition is used as a reference point to propose an expanded AM definition framework. Using visualizations, this paper explores Venn diagrams, parallel coordinates plots, and the relationship mapping tools. The major contribution of this work is on the use of visualization models to unravel AM definitions and speculate on possible future applications of expanded AM spaces.

The paper is structured as follows. Section 2 outlines the research methods used in this study. Section 3 discusses the results of the proposed definition frameworks and AM outliers. Section 4 presents our conclusions and provides an overview of the future research direction of the study.

II. Methods

This study comprises of three key elements. Firstly, we su rvey 150 definitions of AM from the literature using AM and 3D printing as keywords. The list of AM definitions is considered in verbatim to analyze the exact words used to define AM. To visualize the results of this analysis, we explore three visualization methods. The Venn diagrams (VD) consist of closed shapes in a two-dimensional plane where each represents a category as shown in Fig. 1(I). In this model, overlapping circles and color codes represent the relationship between categories. As shown in Fig. 1(I), VD represent phrases adopted from the ASTM AM definition [6]. To survey the definitions, 150 AM definitions are analyzed on the VD by plotting the code numbers of each definition in the

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dimension spaces. 78% of the AM definitions used in this analysis were published within the last three years (*a list of 150 definitions used can be provided on request).* While the use of VD is used in this study as a quick way to check compliance of AM definitions against the established ASTM AM definition, the model is limited in visualizing high dimensional and multivariate data. Hence the study used the ASTM phrases to develop another model based on the parallel coordinate plots.

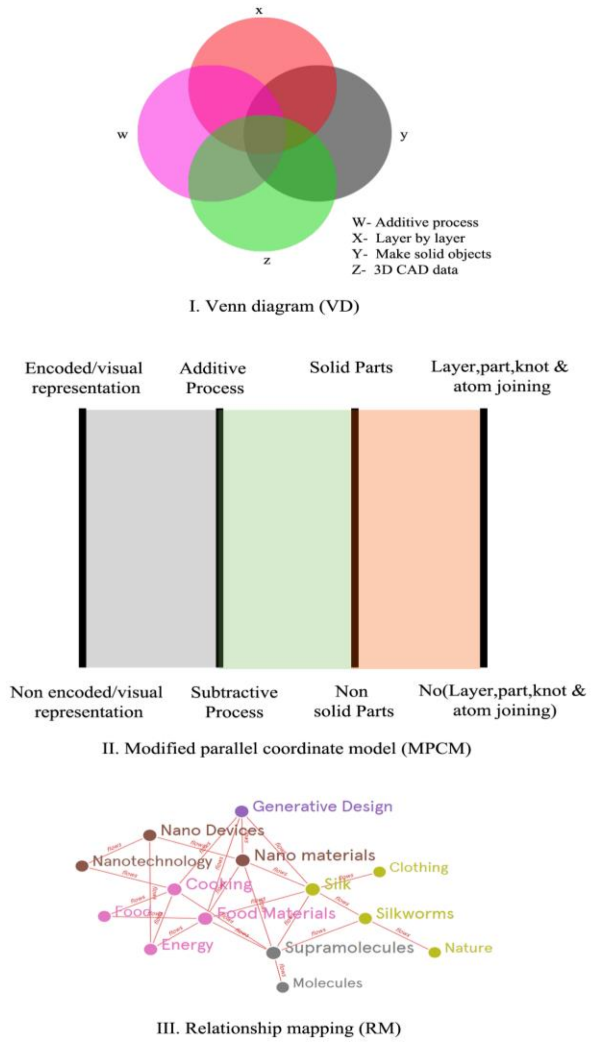


Figure 1. Three visualization methods used in this study. (I) Venn Diagram (VD), (II) Modified Parallel Coordinates Model (MPCM), (III) Relationship Mapping (RP).

As shown in Fig. 1(II), the next visualization method considered is a modified parallel coordinate model based on the parallel coordinate plots theory [11], [12]. The MPCM demonstrates relationships amongst data points across dimensions associated with AM as opposed to VD which only categorizes data by mapping on intersections. The model is used to represent high dimensional and multivariate data in simple 2D patterns [11]. Equal spaced vertical lines are drawn to represent four phrases of the ASTM definition as shown in Fig. 1(II). The data points in the dimension spaces are represented using polylines, with different colors to depict different processes. The visualization is related to time series plots albeit the data is not time dependent. This model is based on a non-cartesian coordinate system and allows one to see many dimensions in a single plane [11].

The MPCM, is used to discuss the manufacturing activities found in Botswana which are not traditionally classified as AM, yet they have similar attributes that may benefit from an expanded definition. These processes and other organic processes such as spider webs and honeycombs are analyzed on MPCM. To expand on the original understanding of AM definition, where manufacturing is purely based on CAD files, the study proposes additional phrases such as parts, slice, knots, and atoms to the dimensional spaces of MPCM. These phrases are an extension to the layer by layer phrase. Furthermore, the 3D CAD data is expanded to a visual/encoded representation of data. The scope of AM may be augmented by simple forming objects additively through joining parts, slice, knots, and atoms using encoded representations. The additional phrases on the MPCM may lead to new ways of manufacturing additively without over-reliance on CAD data.

Secondly, the study uses the MPCM to compare a list of AM outliers. The idea to look at AM outliers is inspired by Gladwell's concept of outliers [13], he posits that these are extraordinary people, and it is essential to identify them and investigate hidden factors that contributed to their success. In [14], outliers are defined as data points that are different or outside the majority clusters. Likewise, AM has outliers which contribute indirectly to its evolution. These outliers indirectly interrelate with AM. As shown in Figure 1(III), Supramolecular chemistry, nanotechnology, silkworms, cooking, and generative design are some of the AM outliers identified and discussed using the expanded definition model. This is done to explore the role AM outliers might have in the future of AM.

Finally, the relationship mapping (RM) is used to establish how AM outliers interconnect and interrelate to speculate on the future forms of manufacturing as shown in Fig. 1(III). The computational tools, i.e. Gephi and python software are used to visualize interconnections between outliers [15]. These interconnections expand the AM landscape beyond the traditional AM practice and open platforms for new thinking. Finding these interconnections between outliers might de-emphasize over-reliance on CAD-based AM software to make space for new ideas, new forms, and experiences to emerge.

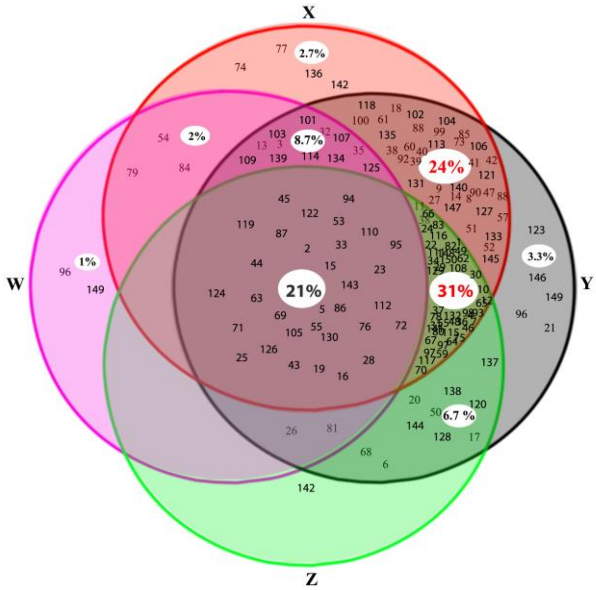
In the following section, results from the VD, MPCM, and RM are presented and discussed.

III. Results and Discussions

A. *Venn Diagram Model (VD)*

As shown in Fig. 2, out of 150 definitions studied, only 21% of the authors comply with the ASTM standard definition of AM, the rest of the 79% seem to have used their own words to define AM. 31% of the studied definitions satisfy the three elements of the VD. An example is taken from one of the definitions studied, Silva and Rezende (2013) defines AM as;

'*AM encompasses a broad class of processes based on continuous deposition of material,* ***layer-by-layer*** *until a* ***physical object*** *is automatically built following instructions from a computer through a virtual model designed in a* ***Computer-Aided Design (CAD) system***.'



Intersectional analysis of data

1. X= 2.7%	5. X + Y = 24%	9. W + X + Y = 8.7%	W + X + Y + Z = 21%
2. Y= 3.3%	6. Y + Z = 6.7%	10. X + Y + Z = 31%	
3. Z= <1%	7. Z + W = 0%	11. Y + Z + W = 0%	
4. W= 1%	8. W + X = 2%	12. Z + W + X = 0%	

Figure 2. AM definitions analyzed using the Venn diagram (VD) circles labelled as Additive process (W), Layer by layer (X), Make solid objects (Y), 3D CAD data (Z).

This definition only satisfies the layer by layer, 3D CAD data and making solid objects elements of the VD, no reference is made to additive process or comparison to subtractive processes. 24% of the definitions use two phrases from the ASTM definition that is the layer by layer and making solid objects. An example is taken from Godoi, Prakash and Bhandari (2016), who define AM as;

'*One of these methods that involve techniques applied for* ***building physical parts*** *or structures through the deposition of materials* ***layer by layer***.'

The latter definition does not refer to additive process or at least compare to subtractive processes and there is no mention of 3D CAD data. 8.7 % of the definitions use three elements with the exclusion of 3D CAD data. An example is taken from Burnham-Fay, Le, Tarbutton, and Ellis (2017), as follows;

'*Additive manufacturing is described as the addition of material to* ***build a structure*** *in* ***sequential layers***, *as* ***opposed to traditional manufacturing*** *where the material is removed from the desired shape'*

The above definition does not mention the use of 3D CAD files. 6.7% of the studied definitions only cover making solid objects and 3D CAD files. An example is taken from Hashemi Sanatgar, Campagne and Nierstrasz (2017);

'*Additive manufacturing is defined as the term used to define a technology applied for the rapid prototyping or rapid manufacturing of* ***3D objects*** *directly from* ***digital computer-aided design (CAD) files***.'

The rest of the definitions mention one of the four phrases of the ASTM definition. 3.3 % use solid objects and 2.7 % use layer by layer process only. See definition examples by Shao, Zhao, Lin, He and Wu, (2017), and Yao, Moon, and Bi (2017) respectively;

'Additive manufacturing (AM) also known as rapid prototyping (RP) technique, allows for rapid fabrication of ***three-dimensional shapes*** *with complex geometries'*

'Additive manufacturing (AM) is an emerging advanced manufacturing technique whose working principle relies on the progressive ***layer-wise material*** *consolidation from the bottom to top'.*

The varied definitions of AM may confuse people, especially when encountered by novice makers and entrepreneurs. Defining AM without giving reference to subtractive technologies may confuse someone, let alone without mentioning the layer by layer process of manufacturing and building solid parts from a 3D CAD data file.

In the following section, the study discusses the results of the modified parallel coordinate model, where the definition of AM is expanded to assess extended processes of manufacturing found in Botswana and elsewhere.

B. Modified Parallel Coordinate Model (MPCM)

AM ASTM processes (e.g., VAT polymerization, Material jetting, Binder jetting, Material extrusion, Powder bed fusion, Sheet lamination, and Directed energy deposition) appear at the top of all dimension spaces in Fig. 3. These ASTM processes are compared to extended methods of manufacturing. ASTM AM processes are based on the CAD file data which is additively transformed into physical or solid objects.

As shown in Fig. 3, under the encoded/visualization vertical axes which form the first dimension of the expanded definition, cluster A represents a group of biological processes which are close to CAD based ASTM AM processes. These biological processes include spider webs, honeycombs, bird nests, ant hills, and silkworms. Unlike CAD based manufacturing processes, these biological creatures depend on their encoded information and visual sensory data stored in their genes to additively create objects of perfect symmetry usually through layer-by-layer, part-by-part, knot-by-knot, and atom-by-atom process [16], [17]. Below cluster A, is a group of human-based methods of making objects such as thatching mud houses, cooking, building mud houses, making wooden toys, ploughing activities and kraal manufacturing. These activities are based on human traditions passed from generation to generation and learned through doing. As shown in Fig. 3, human activities are based on less accurate data than biological creatures. Human reproduction appears at the bottom of the axes, and this is because humans do not have an idea of what kind of babies they will have before birth. The shape and form of babies are beyond human manipulation. The first dimension maps the source file for making objects against CAD-based data.

Under the second dimension of the expanded definition, cluster B represent the human-based processes which are common in Botswana rural communities. These processes include knitting, weaving, kraal making, and thatching. In the second dimension, Cluster B is distanced from ASTM based processes because the techniques combine the additive and subtractive processes. However, most of the biological processes such as honeycombs and spider webs appear close to ASTM processes on the second axes because they follow an additive process. Nevertheless, ploughing is entirely an outlier data point signaling that it does not follow the additive but subtractive process. The second-dimension space maps the processes against ASTM standard based processes.

As shown in Fig. 3, cluster C represents the formation of solid objects or parts which are built through loose or movable parts and joints. Cluster C objects are easily disjointed compared to the ones close to ASTM based AM objects. Processes under cluster C include spider webs, kraals, thatching, weaving, and knitting. The outlier point plotted in the third dimension of AM definition is the painting process, though it follows a layer by layer process, it does not yield a solid object or part.

Cluster D represent processes that are achieved through layer by layer, part by part, knot by knot, and atom by atom techniques. This cluster includes thatching which is a layer by layer process of joining reeds or grass to cover the roof. Kraals are made by joining wooden parts or logs part by part and knitting is done by the repeated intermeshing of loops to make objects knot by knot. The ploughing technique does not follow any of the joining processes shown in the fourth dimension. However, cooking processes are plotted at the center because they partly involve the joining or disjoining of atoms and molecules using heat.

Consequently, the expanded processes of AM may lead to the following AM definition proposition;

> *'The process of joining, forming or building parts to make solid objects through an encoded or visual representation of ideas, layer by layer, part by part, knot by knot or atom by atom as opposed to subtractive manufacturing processes.'*

Expanding the definition of AM allows designers to think in a broader sense which may potentially lead to innovation and new kind of AM design methods.

In the following section, the paper discusses the new spaces which may be created through interconnections between the extended AM definition and some selected AM outliers.

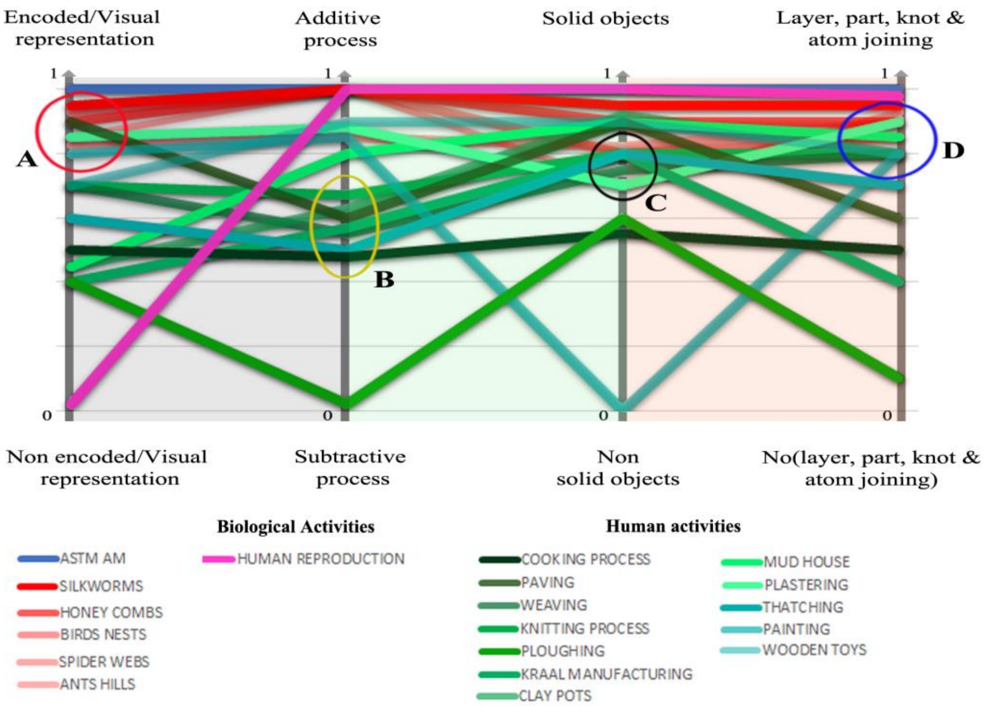


Figure 3. Extended AM processes analyzed using the MPCM

C. Relationship Mapping

The relationship mapping is used to speculate on the role of AM outliers in the future of AM development. The outliers used in this analysis fit within the expanded definition of AM as elaborated in the previous section.

As shown in Fig. 4, Silkworm silk may be used as intelligent materials for surface enhancement. The triangular prism-like structure in silk fibers refracts incident light at different angles thus producing a variety of colors [18]. Further exploration of silk may enable surface properties to respond to external stimuli in various ways. To compliment these properties, researchers are already actively making attempts in programming materials and embedding information within materials surfaces [19], [20]. In the future, the study speculates on the rise of the autonomous machines for customization of textile products, and over the counter production of bespoke wearables. The future of textiles will be engineered through 'additive silking' as shown in Fig. 4 (area A).

Generative tools as shown in Fig. 4 (area B) may have a vital role in the future of making objects. Generative codes when combined with AM may have the power to automate form and functionality.

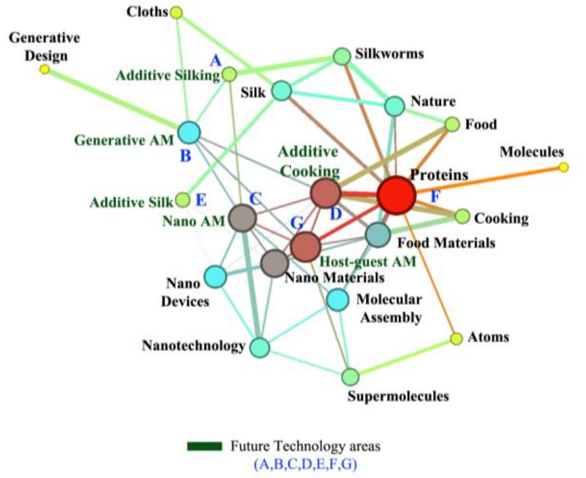


Figure 4. AM outliers relationship mapping: Silkworms + AM→ Additive Silking (A, E), Generative design + AM→ Generative AM (B), Nanotechnology + AM→ Nano AM (C), Supramolecular chemistry + AM→ Host-guest AM (G), Cooking + AM→ Additive cooking (D), Proteins + AM→ Protein additive machines (F).

Through the interconnections shown in Fig. 4, generative AM may be the language of future autonomous manufacturing. Through the relationship between generative AM and Nanomachines, Nanocomputers may drive the autonomy of future kitchens, textiles machines, weaving, pottery machines, and building processes.

Nano AM is a combination of AM and Nanotechnology. This involves joining materials through atom by atom techniques to make objects from encoded data. Area C provides platforms for research in the medical domain in developing and using Nanodevices and Nanoscale features. Breakthroughs in this area will likely improve efficiency in the biomedical and sensing sectors. Efforts are already been made towards this area [21], [22].

As shown in Fig. 4 (area D), Additive cooking is a new area interconnected by AM and cooking processes. This area will likely lead to the development of the futuristic kitchens. While Tesla envisions the next-generation smart kitchens designed to cover all human needs [23], this study speculates on the futuristic kitchens which automate the entire kitchen thus eliminating human interaction with the kitchen hardware. This will likely be achieved by creating an environment where the kitchen becomes the computer loaded with all chemical building blocks for food mixing. Generative tools might play a more significant role in delivering the futuristic kitchens in terms of generating form and customization of food products.

As shown in Fig. 4 (area E), Nano AM is interconnected to additive silk. Currently, researchers are working on feeding silkworms with carbon nanotubes and graphene to enhance the silk properties [24]. In the future, harvesting of fibroin and sericin proteins from the silkworm body before crystallization may be explored to upgrade the silk properties in laboratories. This may increase the control and quality of silk material produced. Future exploration may lead to programming silkworms to deliver silk in a predetermined and entirely controlled way, leading to using these worms to print out desired shapes and objects in a systematic way.

Proteins as shown in Fig. 4 (area F) have high degree connectivity. The future of machines may likely be based on protein manipulation as predicted in [25]. Protein building blocks could play a significant role in additive silk, additive cooking, futuristic kitchens, host-guest AM, and nanomaterial production [26]. While host-guest chemistry is currently used in drug delivery systems as demonstrated in [27], it remains a challenge in building self-interlocking or self-assembling Nanomachines. However, many of this self-assembly Nanomachines will likely be highly prevalent soon as shown by [28]. Relationship mapping is a visualization tool for searching out connections between AM outliers and speculate on how the future of AM might unfold into new areas of innovation.

IV. CONCLUSIONS AND FUTURE WORK

The study presented an expanded AM definition framework by using Venn diagrams, MPCM developed based on parallel coordinate plots and relationship mapping generated using Gephi network visualization tool. The study demonstrated that through visualizations, AM could be extended to explore other manufacturing areas, as thus expanding the landscape of AM research. Further, it was shown that visualizing interconnections between AM outliers can help explore and unravel creative spaces to extend the scope of AM.

Though the definitions studied here provided the basis for this paper, 150 definitions may not be enough to justify the proposed extended definition. A more systematic literature review on wider AM definitions may improve the proposed framework. Another limitation of this study is that the AM outliers are chosen randomly from AM literature, a clear rationale may improve the validity of the extended definition. The major contribution of this paper is the use of visualization tools to propose expanded AM definition models which may be useful for innovation.

As part of the future work, the study continues in the direction of exploring AM innovation ecosystems as a new design strategy. This will be done through public engagement activities. The visualization models proposed here may be used as design tools to explore future additive manufacturing spaces. Further work is now needed to explore local innovation ecologies in developing nations to identify opportunities for novel applications of AM technology which may lead to the development of new methods of additive manufacturing.

CONFLICT OF INTEREST

The authors declare no conflict of interest

AUTHOR CONTRIBUTIONS

Badziili Nthubu conducted the research. He developed the theory and computations. Daniel Richards and Leon Cruickshank verified analytical methods, guided Badziili Nthubu to use visualization tools and supervised the results of the study. All authors discussed and contributed to the final paper.

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