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Nanomaterials For Manufacturing of Functional Prototypes By Additive Manufacturing: A State of The Art Review And Future Research Prospective

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Abstract
Additive manufacturing has considered as one of the advanced manufacturing processes for the manufacturing of highly sustainable functional prototypes. The previous studies have been reported to manufacture different polymers, metals, alloys, and composite materials, which have been shown a wide range of applicability. Also, the use of conventional materials and processes restrict the broad applicability. Nanomaterials are the class of engineering materials that can provide functionality in the products manufactured by additive manufacturing. The previous studies have reported nanomaterials for the manufacturing of sustainable products with a range of functionalities, e.g., sensing abilities, high mechanical performance, toughness, melting behavior, etc. The present study is a state of the art review for nanomaterials in the additive manufacturing process for future applications.

Keywords: *Additive Manufacturing, Nanomaterials, Fillers, Fused Filament Fabrication, Sensor Materials, Functional Prototypes, Innovation*

I. Introduction

In today's manufacturing environment, additive manufacturing is used to manufacture the functional prototypes for automobile, aviation, shipbuilding, construction, biomedical, medical, etc. applications [1]. The previous studies have been reported to manufacture functional prototypes with nanoparticles for the enhancement of the properties [2]. The fused filament fabrication (FFF) or fused deposition modeling (FDM) is one of the low-cost additive manufacturing processes that has shown the potential for manufacturing functional prototypes in different applications [3]. It has been reported that the multi-walled carbon nanotubes (MWCNT) are one of the potential solutions for use as the filler materials in acrylonitrile butadiene styrene (ABS) for enhancement of mechanical and electrical properties [4]. The polycarbonate (PC) thermal conductivity-ABS blend can be modified by using the nanographene fillers [5]. The study suggested that the addition of nanosilica particles on the polyether ether ketone (PEEK)/carbon fiber (CF) coating interface led to modified friction as well as wear properties [6]. The wear behavior of the 3D printed parts can be greatly influenced by hard particles in polymers [7]. It has been observed that the nylon 6 composite feedstock filaments prepared by the addition of Aluminum (Al) and alumina (Al2O3) have shown better wear properties as compared to the virgin polymers [8]. The nanomaterials nowadays can also be used for the manufacturing of lighter products by additive manufacturing technology. The study suggested that increasing the graphene content in the PC-ABS blend has decreased the product's density [9]. The previous studies have been suggested the wide spectrum of application of additive manufacturing with the introduction of nanomaterials in preparation of conductive structures using silver nanoparticles, hydrogels by water-dispersible photoinitiator nanoparticles, the 3D printed polymer structure by silver nanoparticles addition [10]. 3D printing can also be used to prepare the supramolecular composite materials with the addition of nanoparticles. The study has been reported for the 3D printed graphene oxide materials for the lithium-carbon dioxide batteries [11]. Additive manufacturing is also applicable for the preparations of the semiconductor-based composites, magnetic, and photopolymers by addition of nanoparticles [12]. It has been reported that the use of Au, Ag, Cdse/CdZnS nanoplatelets can offer the semi-conductivity in the 3D printed parts by strereolithography (SLA) additive manufacturing process. The studies have also revealed the preparation of magnetic structures by using the nanoparticles in the photopolymers. In the field of biomedical engineering, additive manufacturing is doing a tremendous job for product development. It has been reported that structure controlled antigen can also be prepared using the nanoparticles for vaccine delivery [13]. The antimicrobial 3D printing FFF filaments have also been prepared by adding Ag nanoparticles' fillers. Apart from the biomedical engineering applications, the previous studies have been reported for extraordinary engineering as well as non-engineering applications. For example, the nanoparticles reinforced materials have been used for 3D printing of dichroic nanocomposite material, high strength Al-alloy, nerve repair, self-healing ferrogel etc [14].

It is evident from the literature that nanomaterials are crucial for manufacturing essential and goods in biomedical engineering, sensors making, and other 3D printing applications. The study details the state of the art review for the use of nanomaterials in the additive manufacturing area. The study has been conducted to shows the future research prospective for upcoming researchers and scientists. The areas have been selected to study nanomaterials and additive manufacturing in biomedical engineering, sensor manufacturing, and 4D printing.

II. Biomedical engineering

Nanomaterials are essential materials in the biomedical engineering field. The previous studies related to nanomaterials in additive manufacturing in the biomedical engineering field, the database obtained from www.webofknowledge.com has been processed using the VOSviewer software package.

Putting the keyword "biomedical engineering nanomaterials," a total of 938 studies have been reported. The first 500 studies have been selected for this study. It has been found that previous studies in biomedical engineering have been reported mostly for toxicity evaluation, cell study, proliferation, nanomedicine preparation, cytotoxicity, scaffolds, graphene, hydrogels, graphene oxides, gold nanoparticles, spectroscopy, etc. (see Fig. 1)

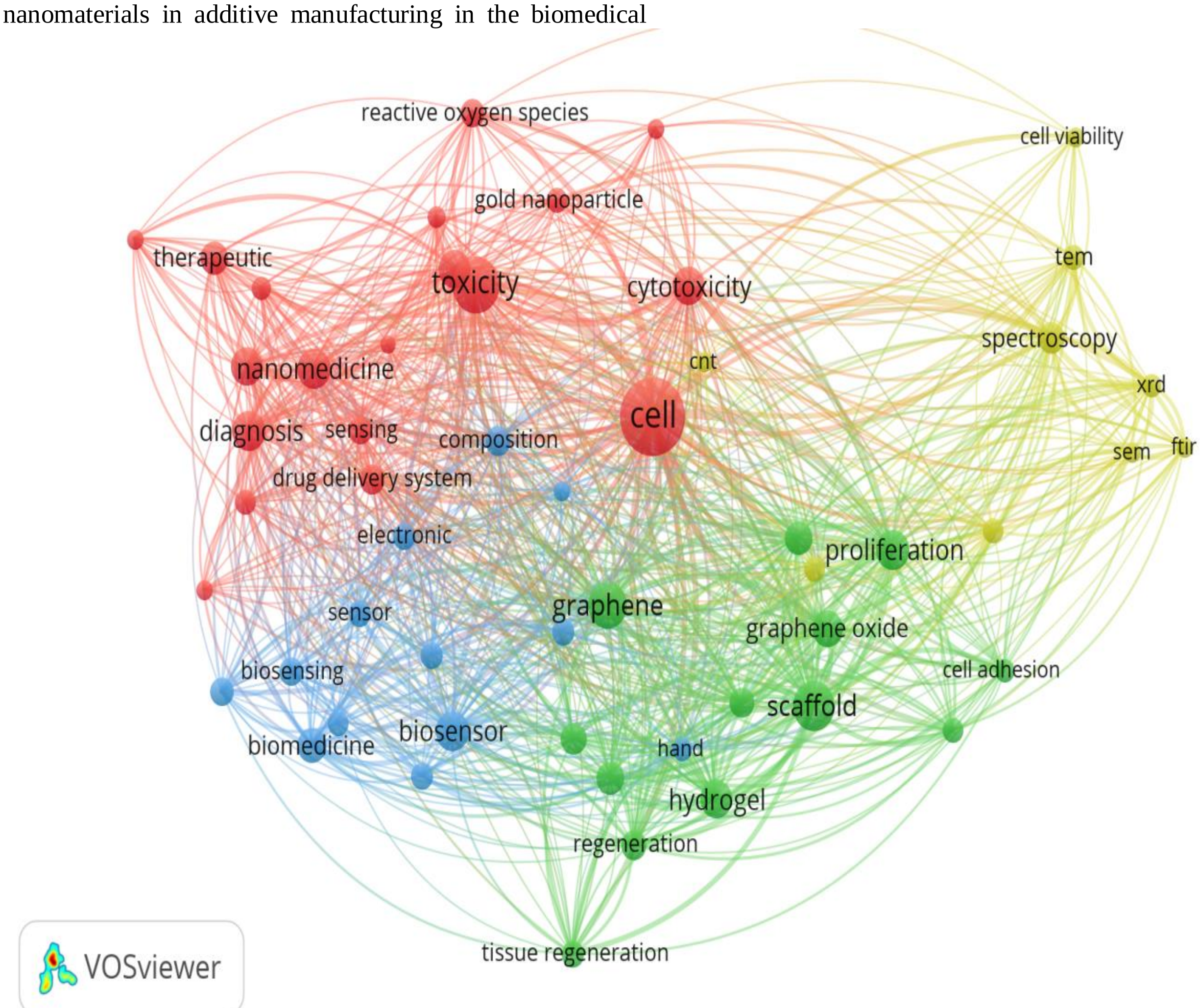

Fig. 1 Bibliographic relational map analysis for keyword "biomedical engineering nanomaterials" (database source: www.webofknowledge.com)

Fig. 2 shows the gap in the studies related to additive manufacturing of scaffold materials using nanomaterials. It relates all terms with the one-term "scaffold" a mapped network obtained, which shows the gap in the studies. It has been observed that a number of studies may be conducted relating to the preparation of scaffolding in biomedical engineering. For example, future studies may be conducted for the scaffolding preparation by additive manufacturing of nanomaterials with the investigations of sensing abilities, potential toxicity, cell viability, using biopolymer, nanomedicine, diagnosis, drug delivery systems, inflammation, etc.

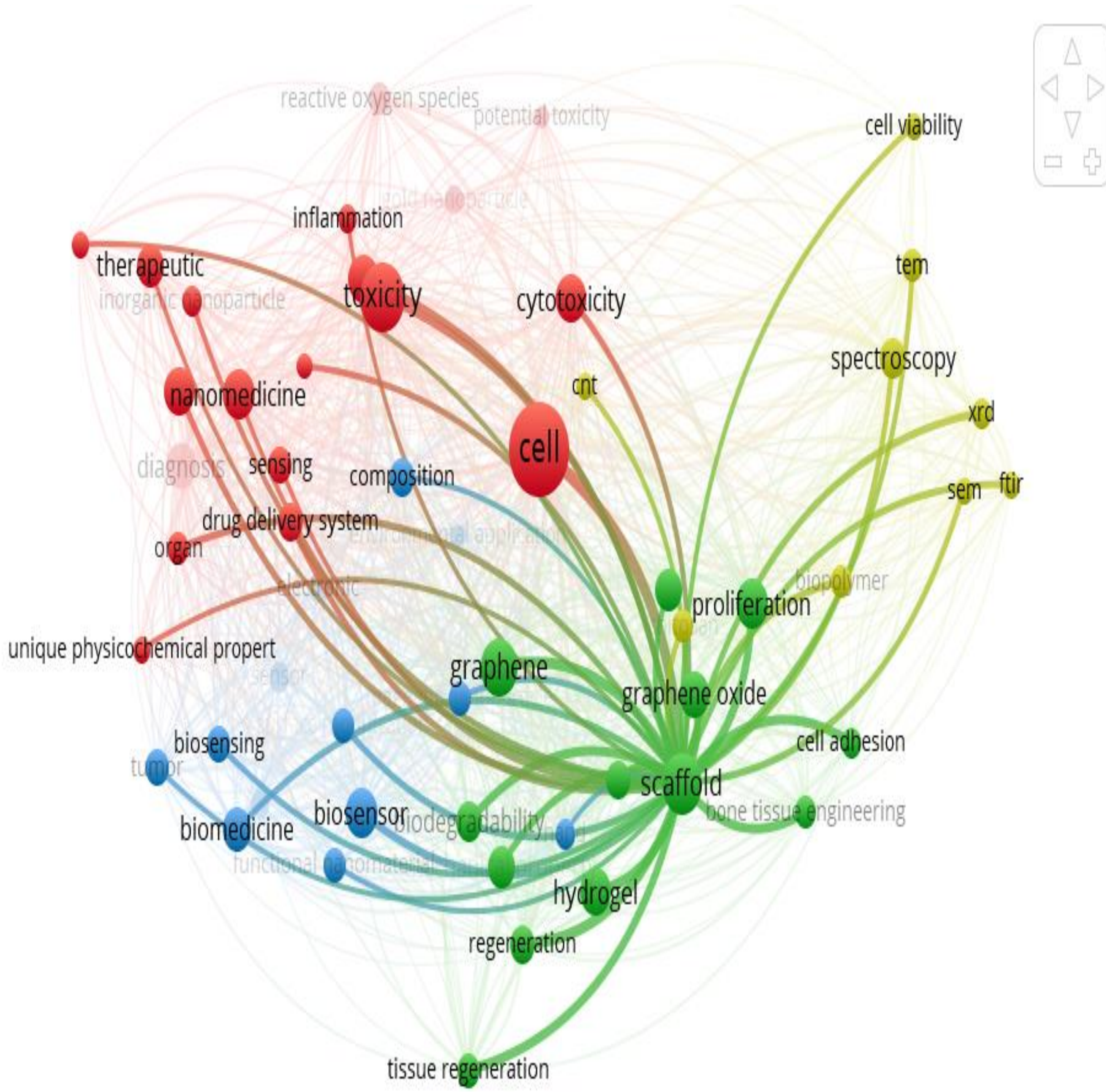

Fig 2. Bibliographic map based gap analysis for additive manufacturing in biomedical engineering

III. Sensor making

For sensor making applications, nanomaterials have revolutionized the sensor making fields. The uses of nanomaterials have been an excellent source for the temperature, gas, fluid, chemical, light, pH, magnetic, and electrical-based sensors. Putting the keyword "sensor nanomaterials," a total of 6987 studies have been reported. Out of those first 500 have been selected for the VOSviwer based relational map analysis. Fig. 3 shows the bibliographic relational map analysis for the keyword "sensor nanomaterials." The previous studies have been conducted for sensing performances and nanomaterial like graphene, gold nanoparticles, carbon dot, etc., for different sensing abilities, e.g., gas sensing.

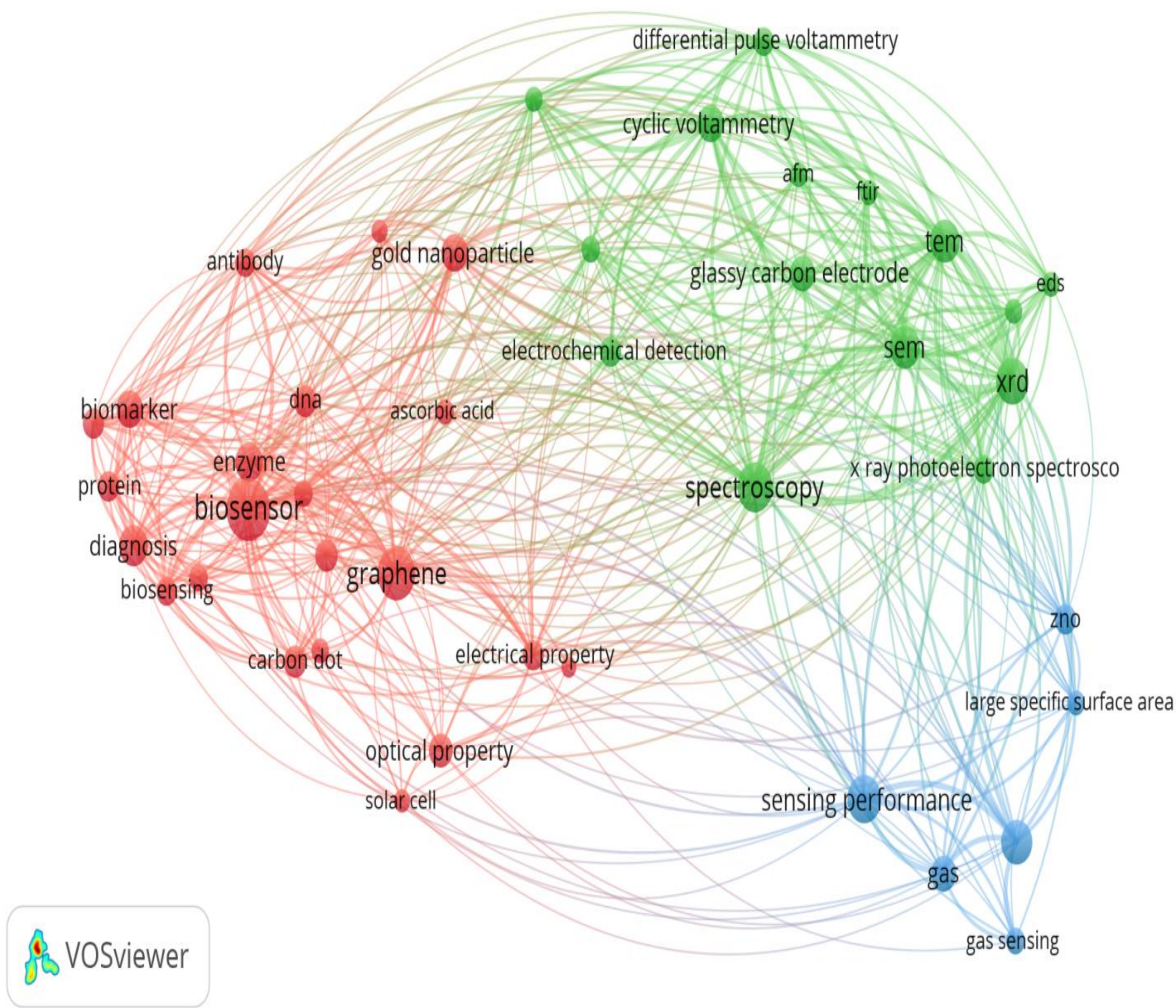

Fig. 3 Bibliographic relational map analysis for keyword "sensor nanomaterials" (database source: www.webofknowledge.com)

Fig. 4 shows the bibliographic map for showing the gap in studies related to the manufacturing of biosensors by additive manufacturing using nanomaterials. It has been found the studies may be conducted in the future for the additive manufacturing of biosensors using nanomaterials for the investigations of atomic force microscopy (AFM), gas sensors, sensing performances, spectroscopy, cyclic voltammetry, differential pulse voltammetry. Using the ZnO nanomaterials in different structural forms can also be taken as the potential additive manufacturing materials for biosensors' preparations.

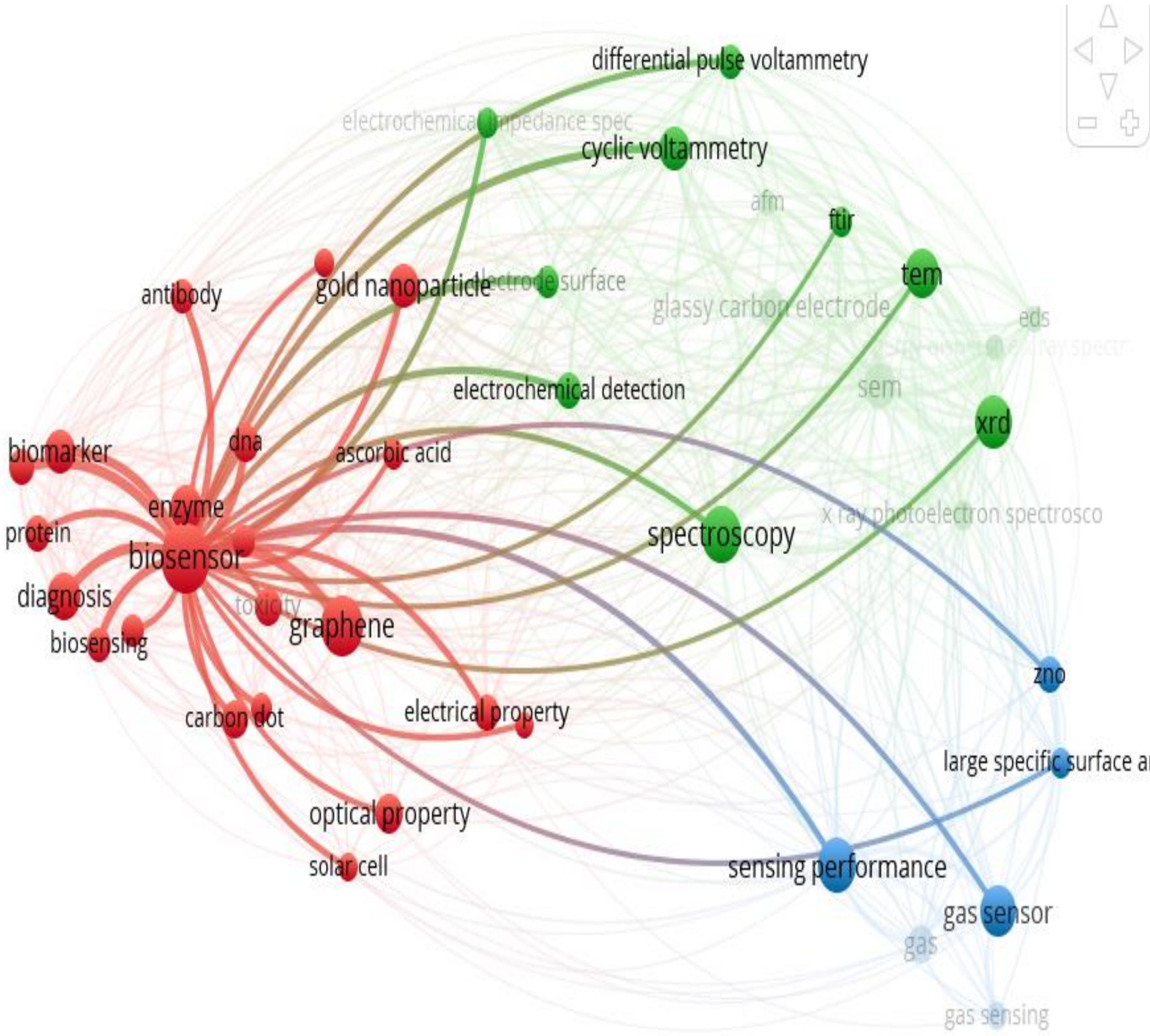

Fig 4. Bibliographic map based gap analysis for "sensor nanomaterials."

IV. 4D printing

The shape-memory materials are the backbone for the 4D printing applications. In the fields of biomedical engineering and sensor make, shape-memory materials play a very important role. The 4D printing process can be accomplished by using shape-memory materials. As per the 'web of science' database, a total of 98 studies have been reported by putting the term "nanomaterials shape memory." VOSviewer software analysis has been conducted to investigate the direction of past studies. The investigations have been made for nanomaterials for shape memory investigations on temperature, resistance, light, etc., the stimulus for the preparation of actuators, nanostructures, devices, nanocomposite, etc. (see Fig. 5).

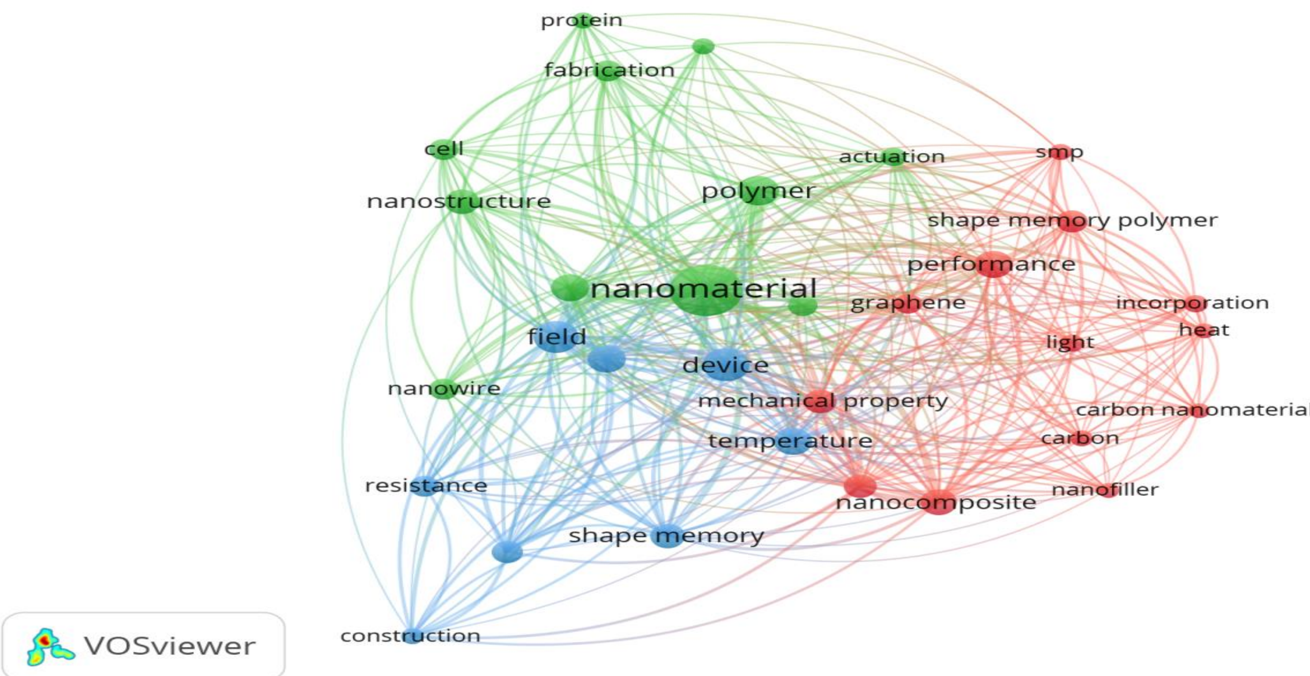

Fig. 5 Bibliographic relational map analysis for keyword "nanomaterials shape memory" (database source: www.webofknowledge.com)

Fig. 6 shows the Bibliographic map based gap analysis for "nanomaterials shape memory." It has been observed that future studies may be conducted for the preparation of shape memory structures by using the 4D printing concept in relation to protein, cell, graphene nanomaterials, polymers, nanofillers, fabrication of functional prototypes, actuators, etc.

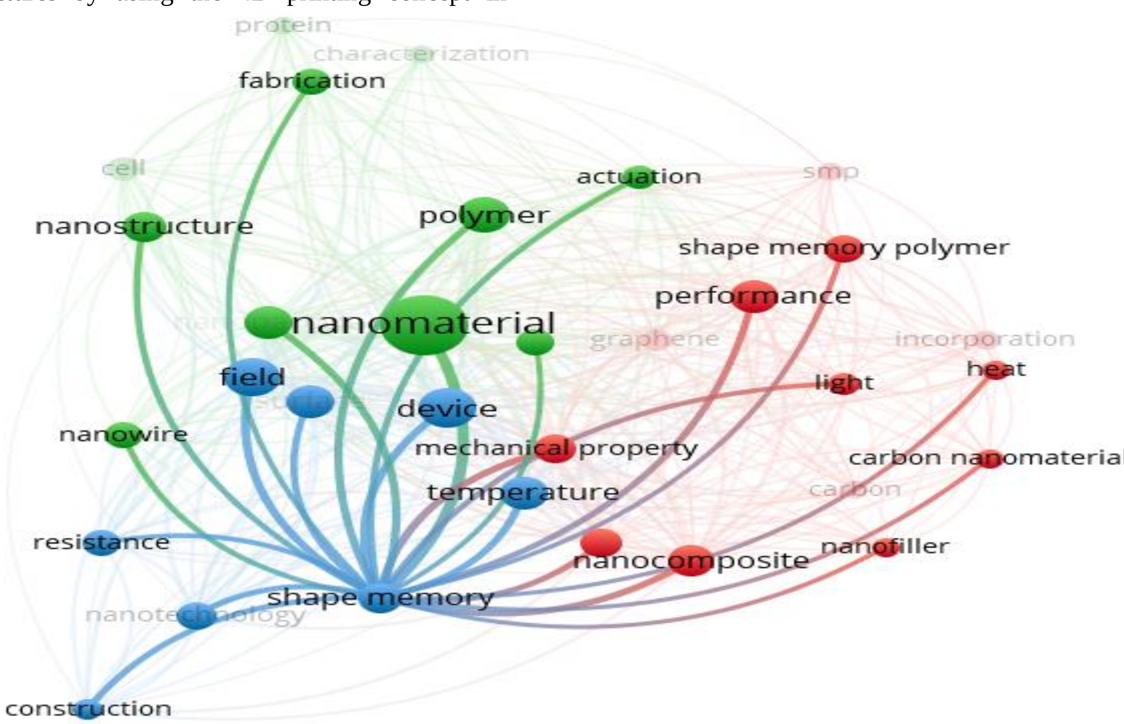

Fig 6. Bibliographic map based gap analysis for "nanomaterials shape memory."

V. Conclusions

Following conclusions have been made for additive manufacturing using nanomaterials for the possible applications in biomedical engineering, sensor making, and 4D printing.

- It has been observed that several studies may be conducted relating to the preparation of scaffolding in biomedical engineering. For example, future studies may be conducted for the scaffolding preparation by additive manufacturing of nanomaterials with the investigations of sensing abilities, potential toxicity, cell viability, using biopolymer, nanomedicine, diagnosis, drug delivery systems, inflammation, etc.
- Using the ZnO nanomaterials in different structural forms can be considered the potential additive manufacturing materials for biosensors preparations.
- Studies may also be conducted to prepare shape-memory structures using the 4D printing concept with protein, cell, graphene nanomaterials, polymers, nanofillers, fabrication of functional prototypes, actuators, etc.

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