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Article

Exploring Emerging Technologies with Analysis of Bibliographic Data Focused on Plasma Surface Treatment

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Abstract: Research trends and emerging technologies were explored through the Web of Science (WoS) literature of the last decade in relation to plasma technology, especially plasma surface treatment, widely used in all industries. For this, a network analysis using country and author keywords and emerging technology search algorithms, with regard to novelty, fast growth and impact, were used. As a result, we derived 40 keywords in terms of novelty and fast growth. Additionally, with these keywords, we traced the impact based on the citation relationships. Finally, nine keywords which were analyzed to contain many new technological issues were identified by deriving the author keywords included in the relevant documents. It is expected that the new technology fields derived from this paper can contribute to establishing a preemptive R&D strategy.

Keywords: plasma surface treatment; research trends; emerging technologies

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1. Introduction

Plasma technology is being used as a core base technology that can promote the creation of new markets and high added value in industries such as semiconductors, displays, metals, machinery, the environment, construction, space, and aviation. Korea has concentrated its R&D investment in the fields of materials (polymers, heat/surface treatment), electricity and electronics (semiconductor equipment, displays, etc.) and physics (plasma physics, fluid/plasma, etc.). Recently, related studies were expanded to fields such as energy, the environment, medicine and biotechnology. Germany and the United States also extensively studied the industrial application value of plasma technology and are expanding their investments into new industries such as the bio, environmental and agricultural industries, as well as existing industries such as automobiles, lighting, machinery, and semiconductors.

As such, the application fields of plasma technology are very diverse, and the levels of technology required by the industries are also very diverse. For example, the semiconductor field focuses on the plasma simulation technology required for the process and equipment utilization, while the bio field focuses on real-time plasma reaction diagnosis technology. That is, plasma-related technologies are closely related to each other, but have the same characteristics as general-purpose technologies, whose approaches may be very different depending on the method of application and utilization.

Plasma surface treatment technology mainly uses atmospheric pressure plasma to wash away organic materials which accumulate on the surface of metals or polymers through plasma cleaning, or to increase the adhesion with other materials by providing roughness for the surfaces [1]. The scope of applications is very wide in all industrial fields such as automobiles, machinery, electronics, energy and the environment, and competition for the related core R&D is fierce. In order to examine the research trends related to plasma surface treatment, this paper intends to analyze by the country and keyword in which field research is being promoted by utilizing the literature published on WoS over the last decade (Web of Science).

In particular, by considering the characteristics of plasma technology, which are highly used in various fields as a base technology and can be utilized in various ways depending on the applications, as mentioned above, this paper attempts to present a new research topic from a different point of view. To this end, we developed an algorithm that could present emerging technology candidates by applying indicators of novelty, fast growth and impact, and applied it to a plasma surface treatment case. The detailed explanation of these indicators are mentioned in the next section: Methodology.

The emerging research is being actively conducted to find emerging technologies based on the research literature (papers, patents, etc.) and to track and forecast the evolution of technology, especially in the field of science and technology [2–4]. In addition, as the discovered emerging technologies can be used to establish strategies for preemptive responses to future technological changes, an interest in related research is gradually increasing.

The various methodologies used for detecting emerging issues in the field of S&T are explored in [5]. An explorative method was presented to estimate future applications by analyzing the past or present attempts to grasp the development and current status of S&T. Through a framework called TechFARM (Technology Foresight, Assessment and RoadMapping), analytical methodologies including heuristics, data mining, modeling and simulation, and scenario development were structured for evaluating new or existing S&T solutions. In [6,7], a publication-based co-citation relationship was explored to track new topics by analyzing 22 fields. This Japanese research group mainly used direct citation relationships by analyzing the clusters of publications which explored new research topics or analyzed their technological evolution.

SNS-based emerging search term techniques were also studied. In [8], a new topic tracking method called ETT (Emerging Topic Tracking) was proposed to quickly detect emerging issues. Based on the local weighted linear regression (LWLR) for microblog streams such as Twitter and Weibo, the probabilities of the 'novelty' and 'fading' of specific terms were estimated; [9] proposed the methodology for detecting new events based on Twitter data. The method defined a tweet graph based on the similarity of content for tweet terms and grouped related tweets using the Markov clustering algorithm. The events linked by similarity ware classified as an 'event trend line', and the event that appeared first among them was defined as an emerging issue.

The horizon scanning method is generally used to identify new and emerging technology. It includes the combination of online searches using predetermined search terms and suggestions from listening to experts, interviews, and brainstorming to discover emerging issues [10]. However, it is becoming increasingly difficult to synthesize and judge various technological environment data due to the diffusion of digitalization and related information. Therefore, this paper defines novelty, fast growth and impact as the characteristics of the emerging technology [11,12] and proposes an algorithm to measure each index. By applying the algorithm, we could find issues quickly with similar patterns in a large amount of literature in order to try to find emerging technologies [13].

2. Methodology

2.1. The Overview of Data Analysis

In this study, to search for research trends and emerging technologies related to plasma surface treatment, the related literature in WoS for the last decade (2010–2021) was searched and analyzed. The search keywords ("surface treatment" OR "surface modification") AND "plasma" were used, and the total number of documents found was 7728. As mentioned before, we implemented the algorithm to find emerging technologies with three indicators: novelty, fast growth and impact. Especially, it was very important to gather refined bibliographic data to measure those indicators. Even though there exist many accessible databases, we chose the WoS DB which had well-accumulated and refined bibliographic data compared to other journal DBs. With this information, the algorithm was implemented by Python code. As this paper aimed to find emerging technologies, we attempted to gather data for the last decade. If the timespan of the analysis was longer than the last decade, it could help to identify the research trends. However, in the view of emerging technology, well-known keywords that focused on the past are more likely to appear. This is the reason we set the last decade as the timespan of the analysis for this research.

In order to analyze the literature, we explored the quantitative trend of the papers related to plasma surface treatment and conducted network analysis using Gephi with country–author keywords network to find research areas that each country focused on. Then, by analyzing the author's keywords network, the research fields that were being conducted in the plasma surface treatment field were identified, and the implications of these analyzes were studied.

Next, we explored the emerging technology of plasma surface treatment. Through this, we tried to discover in advance the fields that required R&D and commercialization technology development, in addition to the fields currently being intensively researched and developed. In order to search for emerging technologies, we implemented and applied a separate algorithm that could quickly search for keywords that met these definitions in bibliographical information using three emerging issue search indicators: novelty, fast growth and impact. Prior to deriving the technical field, we first introduce the emerging technology field search methodology used in this paper, and apply the methodology proposed in the WoS literature of the last decade.

2.2. How to Explore Emerging Tecnologies

In this study, novelty, fast growth and impact were measured to derive emerging technology candidates. First, novelty was measured through two methods. First, the frequency of occurrence of a specific keyword was not high compared to other keywords, but the frequency was measured as a case in which the frequency increased rapidly at some point in time due to the nature of the time series. To this end, the concept of 'variance' was introduced to each keyword, and the degree of variance in the frequency of the occurrence of the corresponding keyword for each year was calculated based on the average; this calculation could measure the abrupt changes compared to the average.

As the second method of measuring novelty, by measuring the average frequency of occurrence of the corresponding keyword compared to the average frequency of occurrence of all keywords, keywords that already appeared in sufficient quantity in the literature were defined as relatively low in value as emerging technology candidates.

For example, assuming that the average frequency of appearance of all keywords within a specific document set is 45, the average frequency of appearance of keywords in Figure 1a is 44.54 and (b) is 13.69; Figure 1a shows a number that is close to the average frequency of appearance of all keywords; therefore, it has already been sufficiently exposed in related fields, and so its value as an emerging technology candidate is low.

Next, the fast growth was measured based on the acceleration value, which was calculated by introducing the concept of the acceleration of appearance of a keyword, obtaining an acceleration value for the number of appearances of the corresponding keyword for each year, and accumulating it until the last year of appearance. That is, as shown in Figure 2, the a1, a2, . . . , and a5 values of the appearance acceleration for each year were calculated as accelerations of a certain magnitude with a sign of +/− according to the increase or decrease, and by calculating the value of a1 + a2 + . . . + a5. We decided that a keyword with a high acceleration of + value will be considered 'fast growth' in the future.

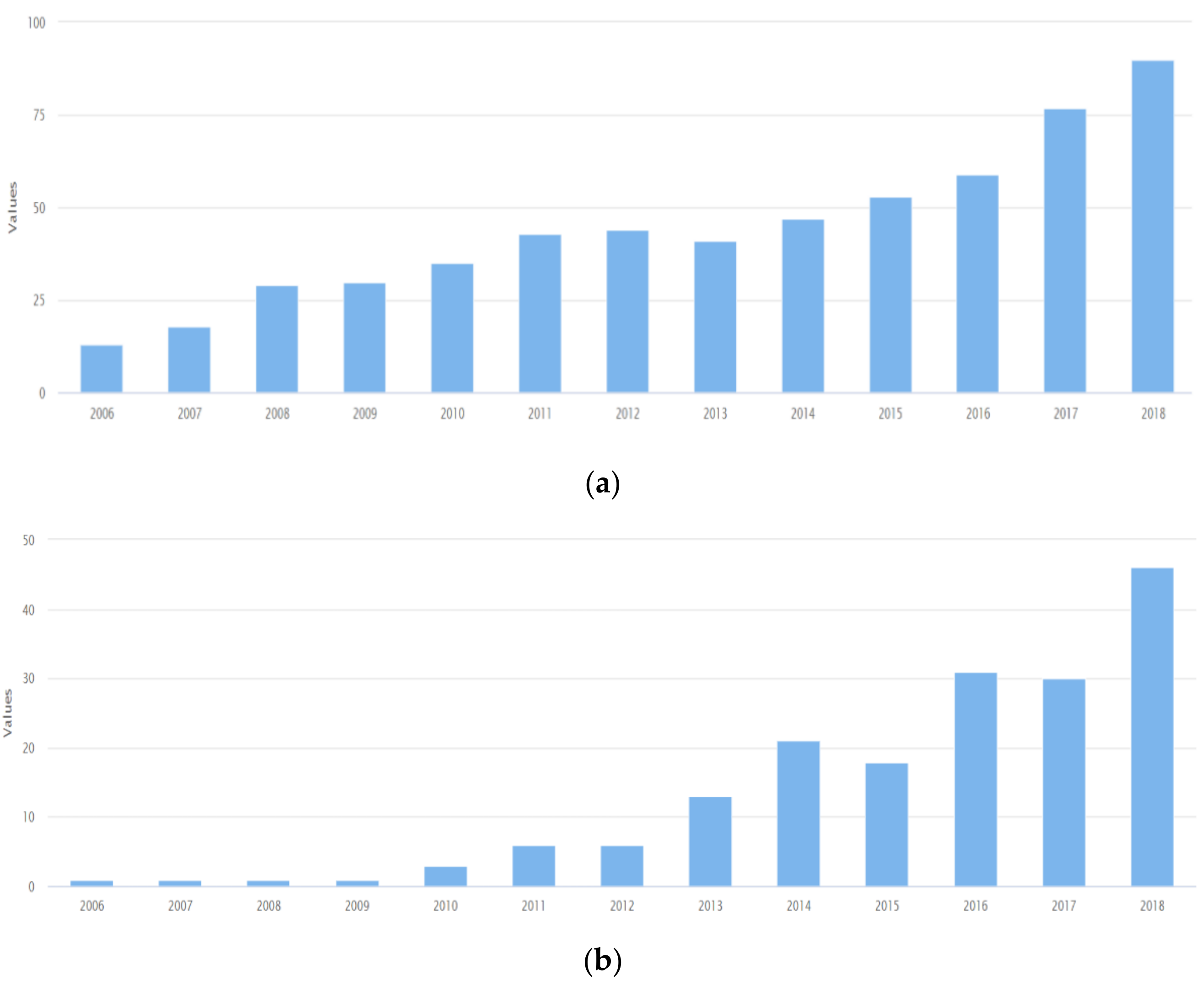


Figure 1. Example of average-based keyword novelty analysis. (**a**) Keyword occurrence frequency 1 (**b**) Keyword occurrence frequency 2.

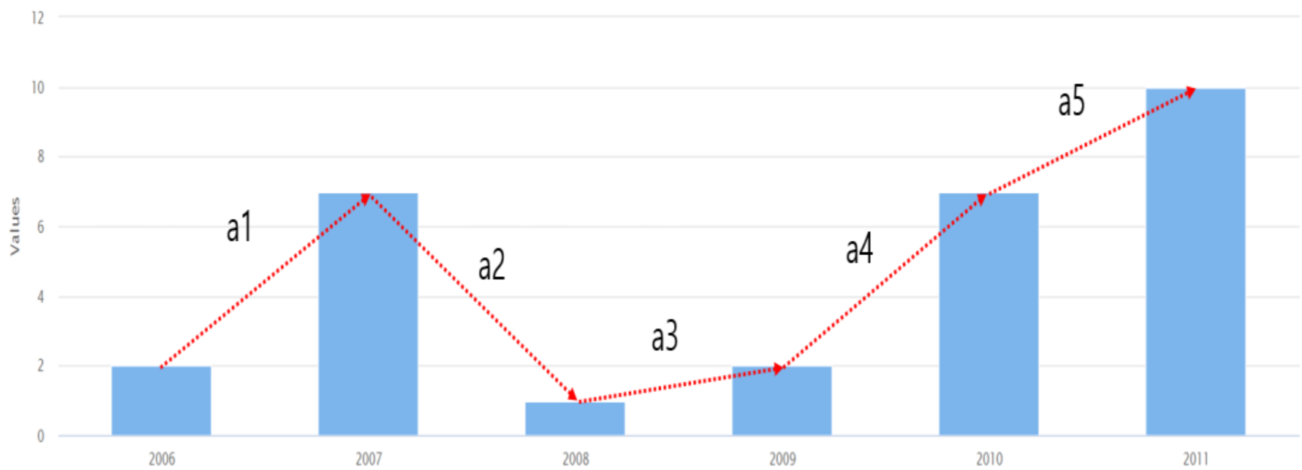


Figure 2. The concept of fast growth analysis using the acceleration of emergence.

Lastly, as shown in Figure 3, impact was measured by the number of the fields propagated from a specific field to another field using the citation relationship of the specific papers. While sequentially searching all the papers in the set of documents to be analyzed, the citation relationship between each paper and the number of fields to which they belonged were calculated from the bibliographic information. We defined that the greater number is the higher impact. Highly propagated papers, their topics, and keywords included in those papers are used to find and discuss emerging technology candidates with experts specialized in relevant fields.

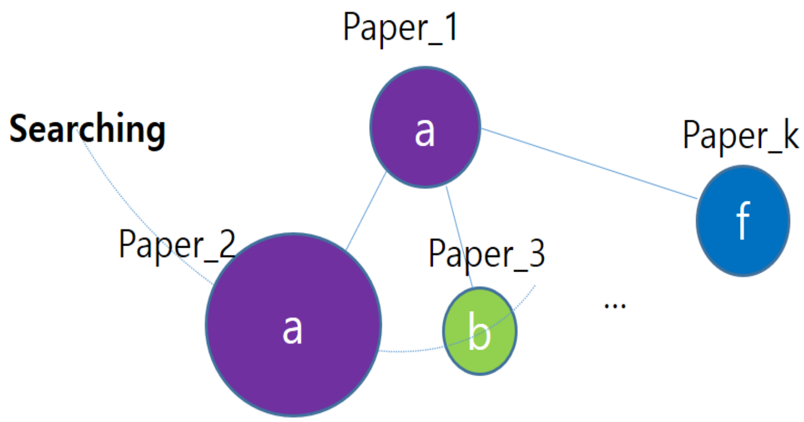


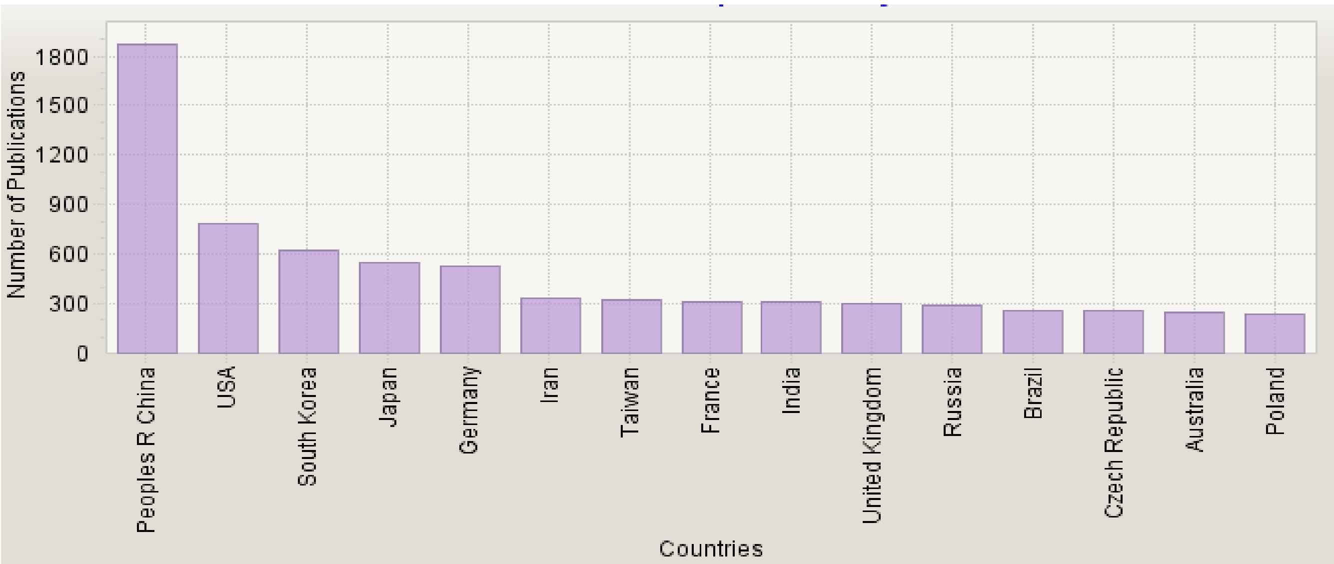
Figure 3. The concept of impact analysis. Node Color means the field of the papers.

3. Results and Discussion

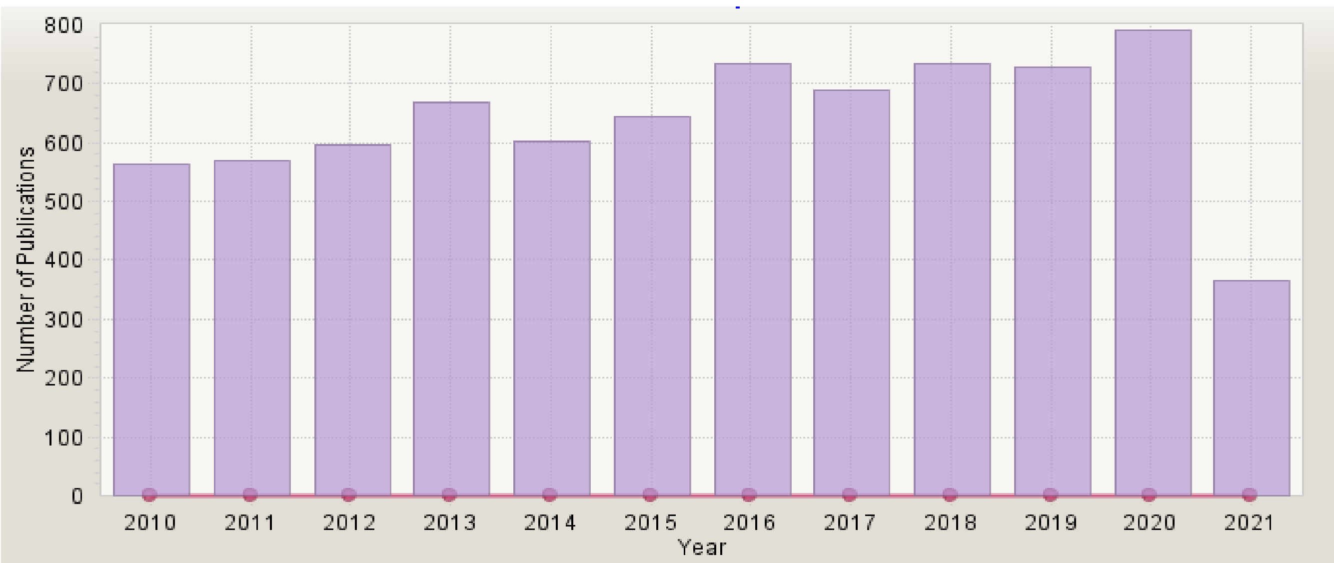
3.1. Research Trends of Plasma Surface Treatment

As shown in Figure 4, more than 500 documents related to plasma surface treatment have been published frequently since 2010, the year of the search, and it can be seen that this trend continues to expand. The country that produces the highest quantity of papers is China, which has produced 1869 documents over the last decade, followed by the United States, Korea, Japan and Germany.

In order to examine the research areas that are being promoted among countries, the country–author keywords (2-mode) network were constructed and examined as shown in Figure 5. For author keywords, only words that appeared more than 10 times were selected and used for analysis. As a result of the analysis, it can be seen that the countries leading the quantitative trend, such as China, the United States, Korea, Japan, Germany and India, are also leading the research in related fields in the network. A distinctive feature is that the majority of research topics are interconnected rather than one country having an advantage in a specific field. In other words, keywords with a high frequency of appearance such as wettability, XPS, Barrier discharge, Plasma polymerization, Hydrophilic, Biocompatibility, Composite, Mechanical properties, Titanium, Biomaterial, Thin film, and SEM were linked with most countries. In addition, countries, such as Italy, France, Czech Republic and Russia, which were not at the top of the list in terms of quantitative trends in the literature, also showed omnidirectional links with keywords with a high frequency of appearance. As a result of looking through the country–author keyword network, it was observed that some countries were leading academically active research on plasma surface treatment technology, but technically, the cooperation and competition between countries could be expected to be fierce.



(**a**)



(**b**)

Figure 4. Quantitative research trends in plasma surface treatment literature. (**a**) Publications per country (**b**) Publications per year.

In order to examine the research trend related to plasma surface treatment more specifically, a one-mode network analysis consisting of author keywords was conducted. Figure 6 shows the network of author keywords related to plasma surface treatment. The node color denotes the sub-field of plasma surface treatment technology. It is analyzed by the algorithm. For example, the keywords of the same color have a high probability of belonging to the same sub-field. As previously seen in the country–author keyword network, the author keyword network also forms very close correlation networks with each other. For example, the XPS with the highest connection centrality can be viewed as a keyword with the most dominant status in the plasma surface treatment author keyword network. As such, XPS is connected with most of the author keywords in Figure 6, and similar trends could be found in the keywords such as contact angle, adhesion, wettability, mechanical properties, surface, hydrophilic, and polymer with a similar connection centrality. Therefore, rather than showing a research field in which the plasma surface treatment technology has a specific advantage among research topics, it is considered to be a field in which research topics are related to each other in all directions.

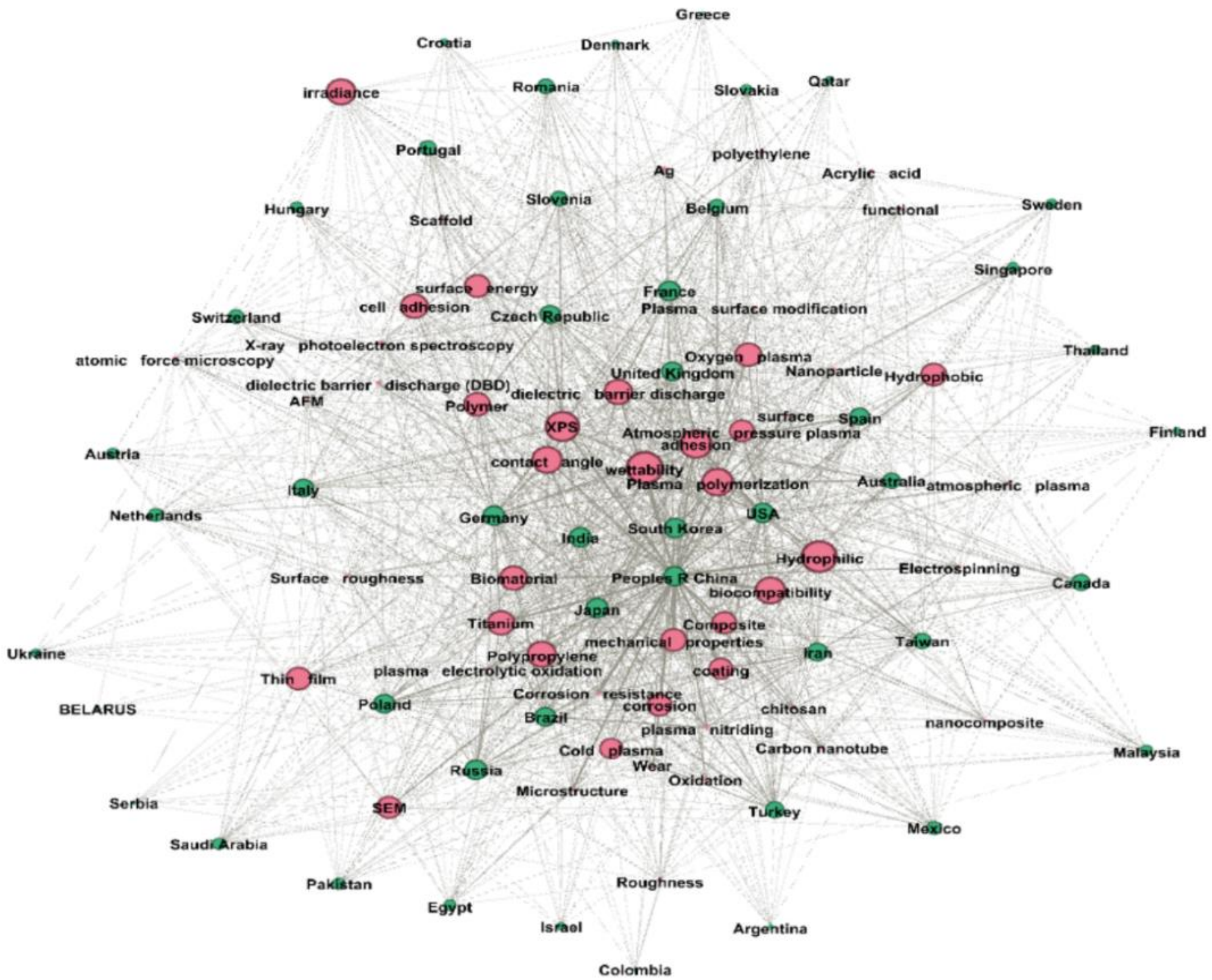


Figure 5. Plasma surface treatment related country (green nodes)–author keyword (red nodes) network.

In the country–author keyword network discussed above, as shown in Figure 7, the sub-network centered on Korea is extracted separately. In the previous major author keyword network, Korea has a high centrality, with keywords such as XPS, Dielectric barrier discharge, Contact angle, Wettability, and Hydrophilic. It is linked with keywords such as Biocompatibility and Biomaterial. In other words, it is understood that the plasma surface treatment field is being carried out in connection with similar research fields all over the world, including in Korea.

In this situation, it is analyzed that it is a very important strategy to make efforts to gain an edge by continuously competing in the already active research field, and to actively discover new technological fields and prepare for them in advance. In particular, the plasma surface treatment field is a technology widely used in all industries, and it is judged that countries and companies can create new growth engines by discovering new technology fields.

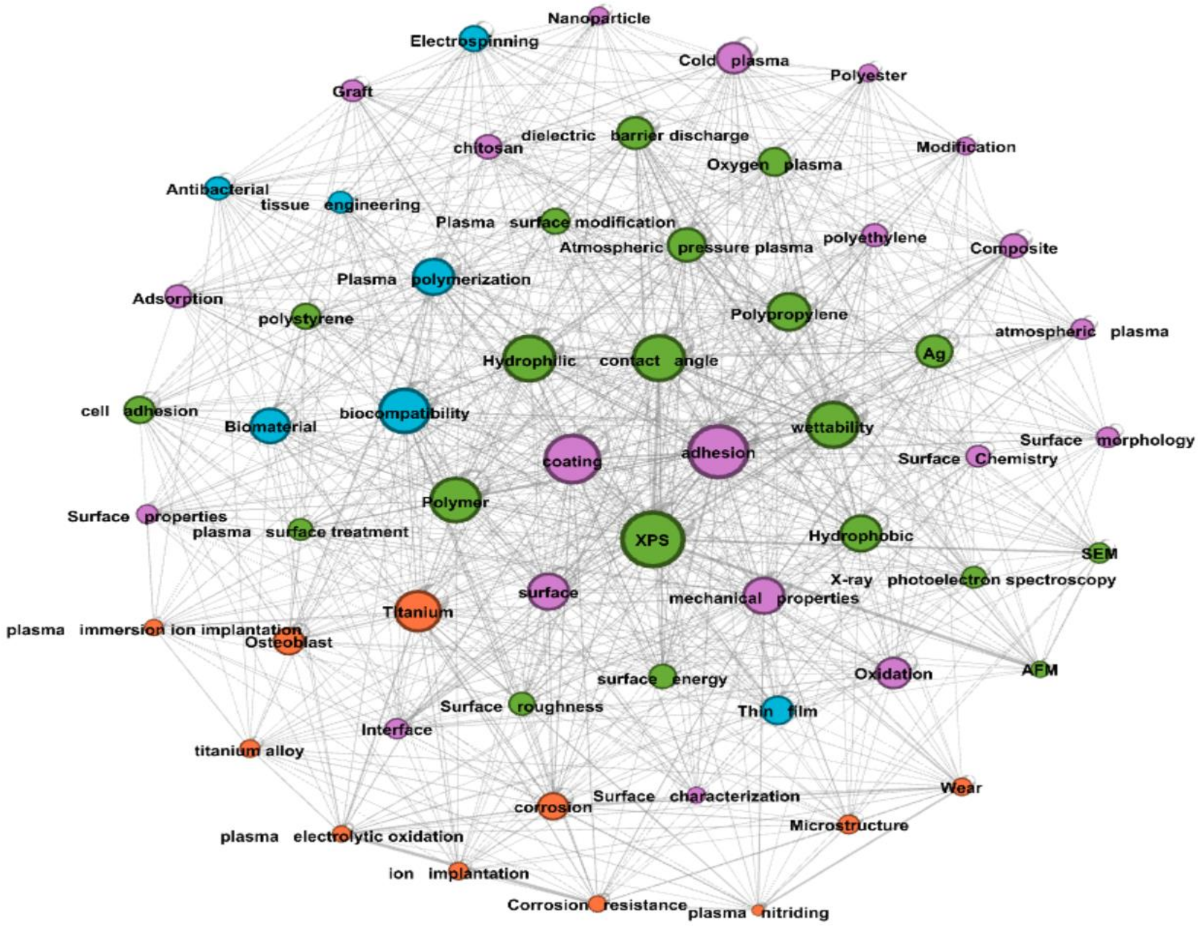


Figure 6. Key author keywords related to plasma surface treatment.

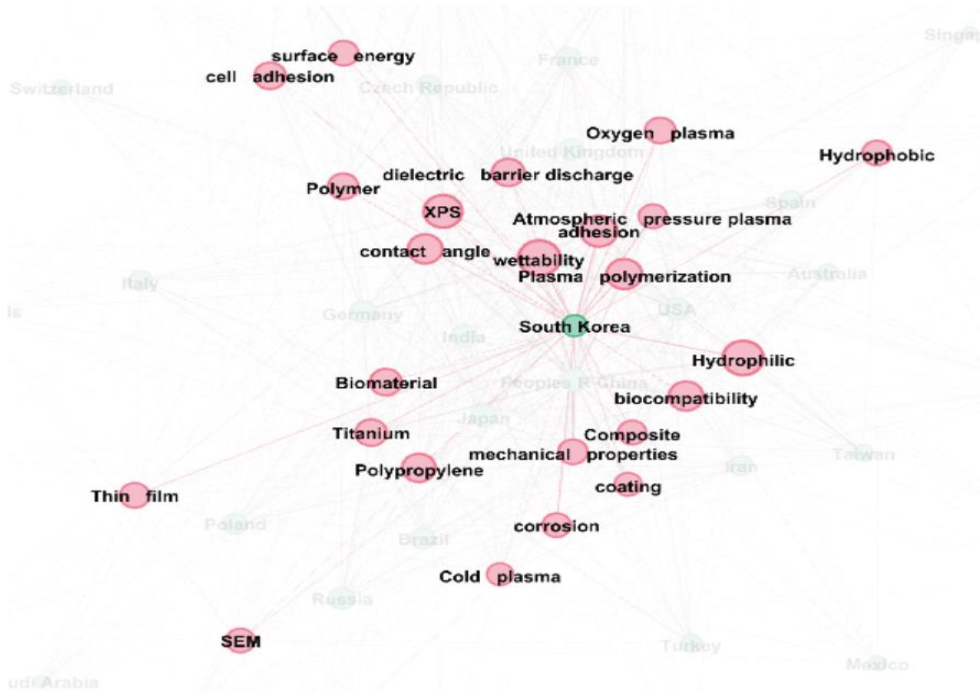


Figure 7. Sub-network 'Korea' of country–author keyword network.

In the next chapter, we introduce the method of exploring, through the proposed index, and discovering new technologies in this regard and examine which new technologies are discovered when the method is applied to the plasma surface treatment field.

3.2. Analysis of the Results of Exploring Emerging Technologies

Previously, research trends by country were reviewed through the author keywords in the plasma-surface-treatment-related literature over the past 10 years. As fierce competition and cooperation take place in similar fields, it seems very important to preemptively discover new technological fields and connect them with competitiveness. In order to discover new technology fields, this paper attempted to derive technology fields with a high potential for future development through the analysis of novelty, fast growth and impact.

First, in order to derive the most optimal emerging technology candidate based on novelty and fast growth, the variance value is maintained at the maximum, and the average frequency of the appearance is set to 1/3 (36 times) compared to the average frequency of the appearance of all keywords (109 times). The top 40 keywords were derived in Table 1 with this high order of novelty and fast growth. In terms of novelty and fast growth, corrosion resistance was identified as the highest priority word, followed by plasma material processing, carbon fiber and microhardness.

Table 1. Top 40 keywords based on novelty and fast growth related to plasma surface treatment.

Rank	Keywords	Rank	Keywords
1	Corrosion resistance	21	Microfabrication
2	Plasma materials processing	22	Bioactivity
3	Carbon fiber	23	Epoxy
4	Microhardness	24	Spark plasma sintering
5	Nanofibers	25	Biofouling
6	Antibacterial activity	26	Epoxy resin
7	Interfacial adhesion	27	Friction
8	Additive manufacturing	28	Surface activation
9	Atmospheric-pressure plasma jet	29	Bone tissue engineering
10	Shear bond strength	30	Biofilm
11	Microstructure	31	Polydimethylsiloxane (PDMS)
12	EIS	32	Air plasma
13	Dental implant	33	DBD plasma
14	Fatigue strength	34	Diamond-like carbon
15	Bipolar plate	35	Cytocompatibility
16	Surface morphology	36	Niobium
17	Polypyrrole	37	Bioactive coating
18	Transmission electron microscopy	38	Superhydrophobicity
19	CFRP	39	Nanoindentation
20	Graphene oxide	40	Silver nanoparticles

Next, the impact on the other fields was measured, and Table 2 shows the top 10 documents that spread the most to the other fields and the number of citations used over the last decade. For example, "Surface modification of polyimide films using unipolar nanosecond-pulse DBD in atmospheric air (2010)" was cited 157 times from 2010 to 2021. Figure 8 shows the impact of the paper in other fields. In 2010, it was cited in four fields: materials science, physics, chemistry and engineering, but in 2019, science and technology, polymer science, and biophysics, etc., were also cited.

Table 2. Top 10 publications with impacts in other fields related to plasma surface treatment. (papers listed in the table refer to [14–23]).

Rank	Paper	# of Citations
1	"Surface modification of polyimide films using unipolar nanosecond-pulse DBD in atmospheric air" (2010)	157
2	"Oxygen plasma treatment for reducing hydrophobicity of a sealed polydimethylsiloxane microchannel" (2010)	121
3	"Surface modification of electrospun PLLA nanofibers by plasma treatment and cationized gelatin immobilization for cartilage tissue engineering" (2011)	118
4	"Surface modification of polymers by plasma treatments for the enhancement of biocompatibility and controlled drug release" (2013)	86
5	"Surface modification and ageing of PMMA polymer by oxygen plasma treatment" (2012)	88
6	"Cold atmospheric plasma: Sources, processes and applications" (2010)	88
7	"Poly (dimethyl siloxane) surface modification by low pressure plasma to improve its characteristics towards biomedical applications" (2010)	128
8	"Surface modification of polymeric materials by cold atmospheric plasma jet" (2014)	74
9	"Oxygen and nitrogen plasma hydrophilization and hydrophobic recovery of polymers" (2012)	61
10	"Surface modification of several dental substrates by non-thermal, atmospheric plasma brush" (2013)	56

In order to synthesize and analyze the novelty, fast growth and impact analyzed previously, the literature with the top 40 keywords for novelty and fast growth in Table 1 was traced and it was determined whether the literature including those keywords had a high ranking in terms of the impact measured. In this paper, the top 50 papers from the impact analysis were used for deriving emerging technologies.

When all indicators such as novelty, fast growth, and impact were comprehensively considered, the measured keywords that were considered to be of high value in the emerging technology in the field of plasma surface treatment. 'Antibacterial activity', 'Interfacial adhesion', 'Atmospheric-pressure plasma jet', 'Dental implant', 'Surface morphology', 'Surface activation', 'Polydimethylsiloxane (PDMS)', 'DBD plasma' and 'Superhydrophobicity' were derived as keywords for the candidates of emerging technology.

Table 3 separately arranges the author keywords included in the literature in other fields over the last decade that cite literature containing the nine keywords listed above. By identifying the keywords in the field that spread to other fields, it is expected that the research subjects will be able to use them to establish new R&D strategies on which fields to pursue research in the future in relation to plasma surface treatment. However, due to the nature of the field of science and technology, it does not spread to a completely unrelated new field, but rather to a related field for the development of convergence technology for application and utilization. For example, 'DBD' literature, has spread the most to the other fields, being applied in the fields of chemistry, materials science, physics initially to imaging science, plant science, optics, food science, engineering, science and technology, polymer science and biophysics.

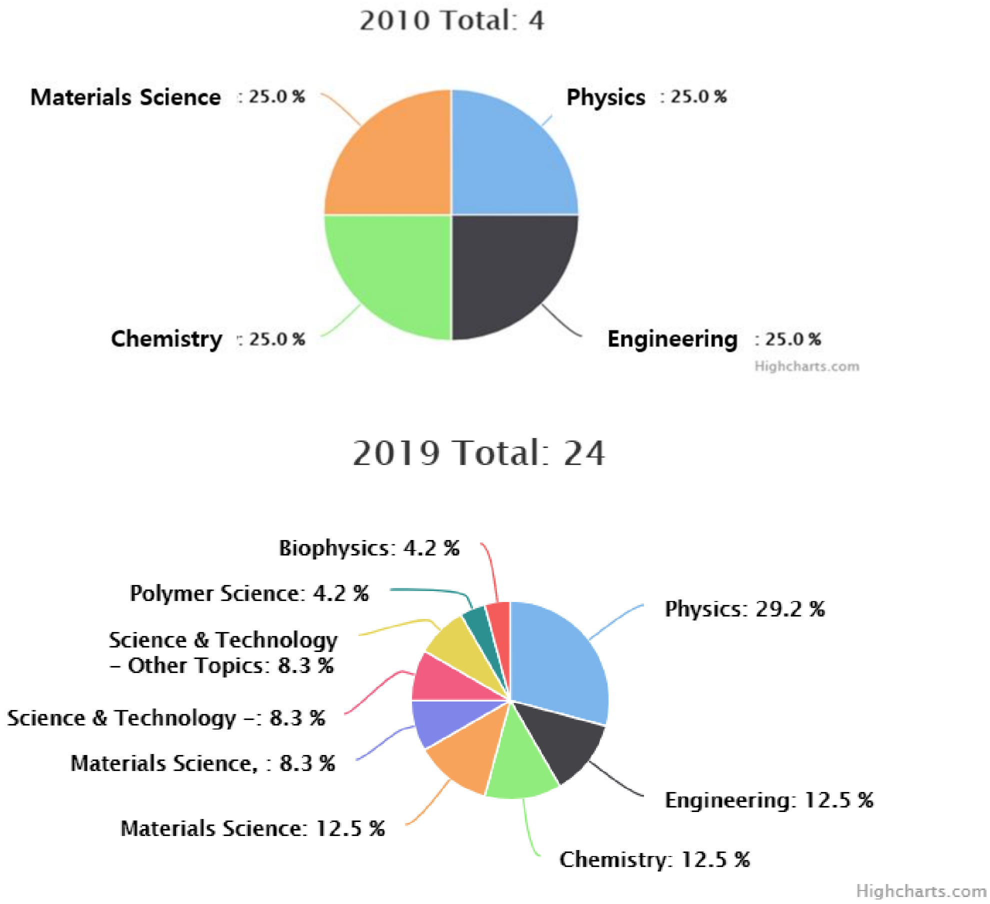


Figure 8. Example of impact analysis of "Surface modification of polyimide films using unipolar nanosecond-pulse DBD in atmospheric air" (2010).

Table 3. Plasma surface treatment of emerging technology candidates and keywords that have spread to other fields.

Emerging Keywords	Keywords of Propagated Fields
Antibacterial activity	X-ray photoelectron spectroscopy, Double langmuir probe, Plasma density, Electron temperature, Debye length, Hydrogen, nitrogen plasma, Poly (ethylene terephthalate), Functional groups, Poly (lactic acid), Tin, Catalyst residuals, Fluorimetry, Polystyrene, CF4 plasma, Surface functionalization, Hydrophobization, Fluorination, XPS, Ps polymer, Endothelia cells, Platelets, Vascular grafts, Biocompatibility, Super-hydrophilicity, Regenerated non-woven cellulose, Oxygen, Mechanical properties, Model system, Wound dressings, AFM, Force spectroscopy, Polymer materials, Optical emission spectroscopy, Oxygen plasma, Functional groups, Graphite, Polystyrene, Protein adsorption, Hos cell proliferation, Printability, Fluoroquinolone, Low-density polyethylene, Wettability, Polymer polypropylene, Neutral oxygen atom density, Initial surface Functionalization, Food packaging, Antimicrobial activity, Active packaging, Gallic acid.
Interfacial adhesion	Air DBD plasma, Surface free energy, Tensile strength, Armos fibers, Wettability, DBD plasma, PBO fiber, Surface analysis, Surface characterization, Wetting behavior, Aramid fiber, Treatment time, Fiber tensile strength, Interface properties, PBO/PPESK composite, Carbon compounds, Electrochemistry, Conducting polymers, Properties and characterization, Functionalization of polymers, Textiles, Interfacial shear strength, Multiscale hybrid fibre, Graphene oxide, Plasma polymerization, Polymer-matrix composites (PMCS), Textile composites, Mechanical properties, Adhesion, Reduced graphene oxide, Polyester, Conductive fabrics, Interface modification, Single-fiber fragmentation, Orthogonal experiment, Surface free energy, Para-aramid, thermogravimetric analysis, Low-pressure RF plasma treatment, FTIR spectroscopy, Specific strength, Meta-aramid, Differential scanning calorimetry, Waste plastic bags, Plywood.

Table 3. *Cont.*

Emerging Keywords	Keywords of Propagated Fields
Atmospheric-pressure plasma jet	Optical emission spectra, Water contact angle (WCA), Treatment distance, Gas discharge, Discharge power density, Polyethylene terephthalate (PET), Polymer surface modification, Wettability, Low molecular weight oxidized material, Dielectric barrier discharge, Hydrophilic modification, Microsecond pulse, Gas discharge, Flashover voltage, Pulsed discharge, Surface flashover, Non-thermal plasma, Pulsed power, Surface charge dissipation, Surface trap, Atmospheric-pressure dielectric barrier discharge, Self-healing, bond pull strength, Polytetrafluoroethylene (PTFE), Solder float test, Microwave laminate, Plated through hole, X-ray photoelectron spectroscopy, Absorption spectroscopy, Silicone rubber, Combined voltage, Converter station, Flashover performance, Nacre, UV radiation, Polymer tube, Hydrophilization, Atmospheric cold plasma, Homogeneous, Flexible plasma jet, Ros distribution, tilted application, Triboelectric nanogenerator, Power output enhancement, O-2 and AR plasma, two-step plasma etching, CF4 free.
Dental implant	Ceramic adhesion, Precursor monomer, Non-thermal atmospheric pressure plasma, Surface characterization, Plasma adhesion, Hydrophilic, Dental wax, Surfactant free, Dielectric barrier discharge (DBD), Polymer-matrix composites (PMCS), Textile composites, Plasma process, IR spectra, Hap, Polyethylene terephthalate, Candida albicans, Early adherence, Heat-polymerized Acrylic resin, Contact angle, Biofilm, Osteoblast, Titanium, Self-adhesive resin cement, Shear bond strength, Micromechanical retention, Implant-abutment surface, Provisional cement retention, Abutment surface modification, RGD peptide, Cell adhesion and proliferation, Fibroblast, Ethanol, Octenidine, Abutment, Chlorhexidine, Zirconia ceramic, UV light, Photofunctionalization, Implant surface, Xenograft, Bone regeneration, Argon, Bovine bone, Hydroxyl groups, Anodization, Superhydrophobicity, Hydrogen peroxide, Mechanized surface, Bone-to-implant contact, Resorbable blast media surface, Osseointegration, Implant dentistry, Raman spectroscopy, Anatase, Surface roughness, Ce-stabilised zirconia, Alumina nanocomposite, Bone, Mechanized surface, Anatase, TiO2, ROS assay, QCM measurement.
Surface morphology	Atmospheric pressure plasma jet, Wettability, Low molecular weight oxidized material, Dielectric barrier discharge, Non-woven fabric, Sonophotocatalysis, Ag nanoparticles, Corona discharge, TiO2 nanoparticles, Polypropylene, Aluminium alloy, Adhesion tape test, Air drag force, Tail gas component, Flow humidity, DBD remote treatment, Pet yarn, Oxygen content, In situ xps characterization, Oxygen atom fluence, Initial stages of functionalization, Time evolution of functional groups, Adhesion, Polyethylene, Laminates, Surface chemistry, Grafting polymer, Oxidative polymerization, Polymer modification, Pyrethrum extract, Polyamide, Cellulose acetate, Supercritical solvent impregnation, 3-hexylthiophene, Gliding arc, Plasma diagnostics, Gas dynamics simulations, Bombyx mori silk fibroin, Drug delivery, Core-shell nanofibers, Polypropylene membrane, Membrane distillation, HJelium plasma treatment, Zeta potential, Nanoclay, Dyeing, Nanoclay.
Surface activation	Atmospheric plasma treatments, Paint adhesion, Wave energy converters, Steel surfaces, Fused hollow cathodes, Osteoblast, Hydrophilic, Surface energy, Scaffold, Biphasic scaffold, Non-thermal atmospheric plasma, Wood, Wettability, Polymer, Nanosecond pulse, Dielectric barrier discharge (DBD), Nonthermal plasma, Adhesion, Metals, Contact angles, Epoxy, Discharge power density, ESCA/XPS, OH radical, DC pulse discharge, Laser-induced fluorescence (LIF), Reactivity zones, Optical emission spectroscopy, Surfatron, Raman spectroscopy, Starch, Microplasma needle set-up, Jet array, Large area processing, Electromagnetic simulation, Bone regeneration, Poly-lactic acid (PLA), Scratch resistance, Electron beam evaporation, Aluminium alloy, Adhesion tape test, He plasma, Optical spectroscopy, Spin coating, Lactic acid, Hydroxyl radicals, Colloidal lithography, Cleaning, Gelatin, Grafting, Biomolecule deposition, Collagen, Protein voltammetry, Corona discharge, Single-crystal silicon, Surface smoothing.
Polydimethylsiloxane (PDMS)	SEM, FTIR, PDMS elastomer, piranha, KOH, Sulfobetaine, Urinary bladder implant, AMPS, Salt deposition, Silicone, Sylgard, Hydrophobic recovery, Image analysis, AFM, Biocompatibility, XPS, Apparent contact angle, Change in the surface energy, Titanium, Self-assembled molecules (SAMS), Histidine, Leucine, Roughness, Poly (dimethylsiloxane), Oxygen plasma treatment, Pressure-sensitive adhesives, Microfluidics, Silica-like thin films, Aging, Ionic conductor, Hydrogel, Self-healing interface, Extrusion printable hydrogel, Spray dryer, Flux adhesion, Powder, Condensed matter physics, Cell proliferation, Rapid prototyping, Stability, Endothelialization, Varying crosslinking density, Bone marrow stromal cell, Long-term cell culture, Capillary microfluidics, Geometrical valves, Spin coating, Desalination, Solar still, Graphene.

Table 3. *Cont.*

Emerging Keywords	Keywords of Propagated Fields
DBD plasma	Argon plasma, Adhesive performance, Para-aramid fiber, Fibers, Interfaces, SEM, XPS, Twaron fiber, Plasma-induced coating, Polysulfonamide, Dyeability, Liquid droplet, Interfacial adhesion, Dopamine, Silane, Aramid/rubber composite, Plasma-induced coating, Paper strength, Vinyl epoxy composites, T-peel test, Woven aramid, Impact test, Adhesion pull-off test, CNF, Electric field distribution, Glow discharge, Quasi glow discharge, Polyester, Energy compression, Dischargetime-regulated power source, Polymer films, Supercritical CO2, Ionic liquid, Aromatic polyamides, Kevlar fibre, Silicone, Thermogravimetric analysis, Low-pressure RF plasma treatment, FTIR spectroscopy, Meta-aramid, Differential scanning calorimetry.
Superhydrophobicity	Plasma immersion ion implantation, Mesenchymal stem cells, Polytetrafluoroethylene, Osteogenic differentiation, Polylactic acid, Cell proliferation, Cell adhesion, Biomedical polymers, Biomaterials, Ti-based alloys, EPTFE, Plasma power, SLA-treated titanium, Cellular activity, Dental implant, Biocompatibility, Magnesium alloys, Genotoxicity, Bioactivity, Antibacterial, PEEK, Polydimethylsiloxane, RF plasma treatment, Protein adsorption, Sand-blasting and acid etching (SLA), DC plasma treatment, Amphoteric OH, Multi-functionalization, Covalent immobilization, YTZP (yttria stabilized tetragonal zirconia), Non-thermal biocompatible atmospheric plasma (NBP), MC3T3-EL osteoblasts, dental implants, Tribological properties, Biological and medical properties, Vascular graft.

4. Conclusions

This paper analyzes the research trends of plasma surface treatment technology, which is widely used throughout the industry, and proposes new indicators of novelty, fast growth and impact in order to discover areas that should be focused on as emerging technologies in the future.

The analysis was conducted through 7728 cases of plasma surface treatment related to WoS over the last decade. First, the quantitative growth of literature was led by countries such as China, the United States, Korea, Japan and Germany. However, as mentioned earlier in the characteristics of plasma technology, such kind of properties which connected most of the research topics to each other was also found in the research trend. In other words, rather than a specific country leading a specific research topic, the countries that were not at the top of the quantitative trends such as Italy, France, the Czech Republic and Russia also showed omnidirectional connections. Through this, plasma surface treatment technology is actively leading research in some countries academically, but, technically, it is predicted that the cooperation and competition between countries in relation to the application and convergence of element technology is very fierce.

In this situation, each country should discover new applications and convergence fields related to plasma surface treatment and prepare a response strategy through preemptive R&D preparations. This paper first derived the top 40 keywords based on novelty and fast growth. Next, the impact on other fields was measured based on the citation relationship for all the selected documents over the last decade. Through this, we focused on nine keywords: Antibacterial activity, Interfacial adhesion, Atmospheric-pressure plasma jet, Dental implant, Surface morphology, Surface activation, Polydimethylsiloxane (PDMS), DBD plasma, Superhydrophobicity, which were analyzed as they contained as many new technological fields as possible. In order to propose an emerging technology field related to plasma surface treatment through the process of backtracking the literature containing these nine keywords and, finally, by deriving the author keywords included in the relevant documents.

As a result of the analysis, we could find that some keywords appeared commonly in various fields, for example: Plasma generation, Material, Gas, Diagnosis and Physical properties, and so on. However, a number of keywords showing specialized technologies and even uniquely appeared keywords were also included. Therefore, it is expected that these keywords can serve as a starting point in the process of exploring new research topics and technical fields related to plasma surface treatment in the future.

Since the keywords presented in this paper are author keywords, there is a limitation in not being able to explore the detailed issues of the literature. However, as revealed in the introduction, I think that it is of great significance for this study to be able to quickly search for technologies that are likely to become emerging technologies in the expansion of knowledge and provide them to experts in the related fields.

The characteristics of plasma technology as a general-purpose technology are characterized by fierce competition and cooperation. In other words, it can be understood that someone who quickly occupies the leading technology in this field can lead the trend of the technology. Therefore, I think it will be important to revitalize all-round R&D for plasma technology, which has become an important means for all industries, through the improvement of technological competitiveness in the existing competitive fields and in the preemptive responses to new research fields.

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