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Research Trends in Wireless Communications Using Graphene: Research Trajectories in Antenna Applications

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ABSTRACT

Communications require a large amount of network resources to support the heavy traffic generated by the Internet of Things (IoT). As a result, microelectronics and telecommunications have been exploring types of hardware capable of supporting these new network architectures and communication systems. New devices should be designed to offer high speed, ultra-wideband connectivity, and extensive coverage. In addition, they should use eco-friendly materials to respond to the needs of sustainable smart cities and meet the requirements of future communications. This literature review followed the PRISMA statement to identify research trends in the use of graphene in antennas for wireless communication applications. A total of 168 documents were analyzed, and one of the main findings is a considerable rise in research interest in this topic since 2012, with India emerging as the leading contributor of knowledge in this area. Furthermore, most applications have been developed for the terahertz band, and more recent studies have focused on utilizing MIMO technologies for 5G and 6G communication systems. In addition, most research has observed improvements in the performance and efficiency of antennas designed with graphene, observing in some results up to 9.35 dBi of gain and 97.6% in radiation efficiency for applications in the terahertz band.

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1. INTRODUCTION

Technological advances in communication are often related to the development and evolution of devices that transmit and receive signals and data. Today, wireless communications play an important role in various daily activities (Mohanty, 2017). The growth and development of smart (Alsamhi *et al*., 2019) and sustainable (Tura & Ojanen, 2022) cities demand a large number of IoT devices (Lim *et al*., 2022), which require integrated modules and antennas for internet connectivity. Studies in this field constantly aim to optimize signal processing and miniaturize devices to make them more compact and aesthetically pleasant and reduce their optimized devices' size, appearance, and production costs (Boudjerda *et al*., 2022; Kaur & Sivia, 2020). Most wireless communication systems operate within the microwave frequency range, specifically from 300 MHz to 300 GHz (Davis *et al*., 2023; Mazo Vivar & Velasco Maillo, 2023). Devices that operate within this range can either be active or passive. Passive components such as transmission lines, power dividers, passive filters, resonators, and antennas are essential to wireless communication systems (Balanis, 1992).

Microstrip or coplanar antennas are currently employed in the manufacture of flat microwave devices coupled to wireless communication systems (Ezzulddin *et al*., 2022; Nissanov (Nissan) & Singh, 2023; Yiğit & Karayahşi, 2023). These devices are constructed using conductive materials to ensure optimal transmission and low electrical resistance. The most commonly used materials for this purpose are gold, silver, and copper (Colaco & Lohani, 2022; Ding *et al*., 2020; Harikirubha *et al*., 2021; Kashyap *et al*., 2023; Tao *et al*., 2023). Microwave devices can also be produced on rigid or flexible substrates such as fiberglass, glass, or polymers. An alternative technique involves using two conductive layers connected by pillars and employing air as the substrate (Colaco & Lohani, 2022; Tao *et al*., 2023). Hence, there is a need to explore alternatives in the design of information and communication technology infrastructure devices, such as the utilization of cost-effective materials, downsizing equipment, and optimizing them, as emphasized by Yiğit & Karayahşi (2023). One approach to cost and material reduction in antenna design has been the adoption of flexible and portable electronic devices, such as microstrip antennas or patch antennas. Extensive research has been conducted in this regard, encompassing various surface slot typologies (Elsadek & Nashaat, 2008).

Flexible and portable electronic devices are experiencing a growing demand in the current landscape (Bao & Chen, 2016). These devices find application in diverse fields, including physiological parameter monitoring, textiles, and communication (Huang *et al*., 2015a; Stoppa & Chiolerio, 2014). The flexible wireless sensors employed in these electronic devices can be seamlessly integrated into clothing or directly onto the human body for continuous monitoring of variables like temperature, blood pressure, and heart rate (Catherwood *et al*., 2018). Key sectors such as smart energy distribution (Aziz, 2019; Wangsupphaphol *et al*., 2023), healthcare, and smart cities rely on internet access (Ram *et al*., 2021).

With the escalating trend in the number of Internet of Things (IoT) devices (Luckyardi *et al*., 2022) and connected gadgets, the potential for harvesting energy from radiofrequency sources is gaining traction (Andersson *et al*., 2016). Consequently, to unlock the full potential of IoT, antenna materials that are eco-friendly and cost-effective need to exhibit flexibility (Aparicio *et al*., 2016). In addition to antenna miniaturization achieved through geometric parameter adjustments, another aspect studied in antenna design is the utilization of different materials to enhance radiation patterns, directivity, or achieved power. In the emerging field of flexible and conformal printed antenna applications, graphene plays a significant role due to its one-atom-thick structure, high electrical and thermal conductivity, electron mobility, and mechanical strength (Han *et al*., 2018b). Furthermore, graphene exhibits remarkable elasticity, making it relevant for flexible electronic applications (Ram *et al*., 2021).

Graphene stands out as one of the most promising conductive materials sought for portable printed electronic devices due to its mechanical flexibility and structural stability when compared to other metal-based conductors (Ram *et al*., 2021). Graphene offers cost advantages and accessibility, serving as an eco-friendly alternative material. It can be applied to various substrates like papers, and textiles (Prauzek *et al*., 2018). Graphene represents an intriguing blend of semiconductor and metal properties, possessing soft matter characteristics and being the strongest material (Castro Neto *et al*., 2009; Lee *et al*., 2008). Given these fascinating properties, graphene finds applications in numerous areas briefly outlined in this document (Ram *et al*., 2021).

Graphene-based electronics have paved the way for electromagnetic communication at the nanoscale (Jornet & Akyildiz, 2010). Graphene-based antennas resonate in the THz band (Jornet & Akyildiz, 2010) and deliver strong performance in terms of bandwidth and polarization (Llatser *et al*., 2012a). They reduce the size of tunable graphene reflective cells (Ding *et al*., 2020) and are also employed in beam steering (Carrasco *et al*., 2015). Multilayer graphene is an efficient conductor in microwave antennas with higher gain than copper (Carrasco *et al*., 2015). Multilayer graphene is also employed in tunable THz patch antennas, waveguides, and antennas at different frequencies (Correas-Serrano *et al*., 2015; Elmobarak *et al*., 2017; Jornet & Akyildiz, 2010). Graphene's exceptional electron transport properties make it an attractive choice for the next generation of electronics and applications in energy-related fields (Gomez-Diaz & Perruisseau-Carrier, 2012).

With the advent of nanotechnology, materials such as graphene are now being used for these purposes (Abadal *et al*., 2017; Elmobarak *et al*., 2017; García & Betancur, 2017; Goyal & Vishwakarma, 2018; Khan *et al*., 2019; Vakil & Bajwa, 2014). Similarly, the emergence of 5G technology demands that antennas have greater capacity and higher gain, exhibit a directional pattern, and make more efficient use of the wireless spectrum, considering that the previous generation of antennas did not take full advantage of the available spectrum (Sa'don *et al*., 2019). In addition, conventional antennas are limited in their ability to meet the requirements of new frequencies due to manufacturing and installation restrictions, especially in the smallest sizes. In this sense, the use of graphene holds great potential in solving this problem because it enables the production of smaller and thinner antennas capable of transmitting at higher frequencies (Sa'don *et al*., 2019).

Graphene is attracting research attention thanks to its exceptional thermal conductivity and its mechanical, optical, and electrical properties that are not typically found in other materials (Alfonso & Olaya, 2019; Chen *et al*., 2021; de Dios-Leyva *et al*., 2020; Nag *et al*., 2018; Palacios *et al*., 2010). Graphene is a two-dimensional material made up of carbon atoms in the form of tubes or cavities that enable electrons to travel between 100000 and 200000 cm2/V.s at room temperature. As a result, it can replace conductive materials such as copper (Sa'don *et al*., 2020). Consequently, graphene has been used to manufacture microwave devices (Bahrami-Chenaghlou *et al*., 2023; Benjamin & Miranda, 2022; Chen *et al*., 2023; Kiani *et al*., 2022, Kiani *et al*., 2023; Li *et al*., 2023; Rezaei & Zarifkar, 2023), demonstrating outstanding performance. Additionally, various phenomena in the field of applied physics have been studied using monolayer and multilayer graphene in the high-frequency range, especially in microwaves (Dragoman *et al*., 2015). For example, the widespread extraction of graphene flakes from graphite on a large scale sets the stage for the growth of the graphene industry. At present, graphene is easily obtainable in powder and ink forms, offering a cost-effective option with a purity level of 99% (Ram *et al*., 2021).

Using graphene involves controlling matter at the atomic and molecular scale, which provides important tools for designing and manufacturing integrated nanoscale devices. Such devices promise to revolutionize fields such as healthcare, the environment, and the military industry. For example, graphene-based sensors and electrodes can improve conductivity and power an entire circuit (Sharifi *et al*., 2022; Soleh *et al*., 2023). Graphene thin films have also been employed as strain sensors, as explained in (Jain & Dhanjai, 2013; Liu *et al*., 2023; Singh *et al*., 2022). One experimental study modeled a microwave slot antenna in a coplanar configuration based on graphene. The antenna was fabricated on a 4-inch high-resistivity Si wafer, with a ~300 nm SiO2 layer grown through thermal oxidation. A CVD-grown graphene layer was transferred to the SiO2. The results made it possible to generate two-dimensional (2D) radiation patterns at frequencies in the 8 to 12 GHz range, using a microwave-absorbing material and a metal surface on the back of the antenna (Dragoman *et al*., 2015).

Graphene is a planar monolayer of carbon atoms packed in a 2D honeycomb lattice that functions as a basic building block for graphite materials of all dimensionalities. Graphite has been studied for about sixty years and is used to describe the properties of various carbon-based components (Govindaraj *et al*., 2023; Joshi *et al*., 2023; Martínez-Guerra *et al*., 2009; Papageorgiou *et al*., 2017; Urcuyo Solórzano *et al*., 2021). In addition, graphene has tuning properties, which create a series of vibrational frequency relationships that result in a scale (Papageorgiou *et al*., 2017). Moreover, in the domain of 5G mobile communications, graphene antennas are becoming increasingly popular due to their high speed, easy integration with next-generation communication systems, and small size. Given the resistance of this material, graphene antennas can also be used in IoT systems, as they can withstand high temperatures and are resistant to weather conditions such as humidity, wind, and corrosion. Furthermore, they can be useful for monitoring sensors in hard-to-reach areas for continuous maintenance (Hui *et al*., 2023).

The researchers (Hwang *et al*., 2023) designed two graphene-based dipole antennas that can modify their operating frequency and polarization, which can be useful for a variety of systems working with IoT technology. Multiband antennas have numerous applications in IoT systems because of their ability to integrate different technologies into a sensor system that utilizes a single miniature-sized antenna. This antenna, manufactured with graphene and conductive ink-printed textiles, can support the transmission and reception of data through two different feeding locations, as reported elsewhere (Kumar *et al*., 2018a). Graphene antennas can also be useful in the medical field for monitoring patients' condition by wireless communication or detecting changes in their motor functions. The researchers (Riaz *et al*., 2023), for instance, simulated a fractal-like graphene-based flexible antenna that receives sensitive detection signals from a head imaging system and transmits them over the 5G network for real-time monitoring, analysis, and storage purposes.

Similarly, some researchers (Kumar *et al*., 2018b) presented a graphene-based conductive ink-printed textile antenna for satellite communications operating in the 5.17 GHz to 6.13 GHz range. To avoid low conductivity, several layers of graphene were poured into the substrate, and a radio frequency pin was added to improve the system's transmission. This antenna could have useful applications in the positioning of objects, vehicles, and even people.

Considering the above, the relevance of this research lies in addressing the limitations of traditional materials used in microstrip antennas and exploring the potential of graphene as a promising alternative. Conventional materials such as copper, gold, and silver, while effective in terms of conductivity, present significant challenges in terms of cost, weight, and flexibility, which limits their application in modern electronic devices that require miniaturization and adaptability.

Graphene, with its exceptional properties of electrical and thermal conductivity, high electron mobility, and remarkable mechanical flexibility, offers an innovative solution that can transform the design of antennas and other electronic components. Its ability to efficiently operate at high frequencies, along with its compatibility with flexible substrates, makes it an ideal material for the growing demands of IoT devices and applications in smart cities, healthcare, and advanced communications.

Furthermore, the adoption of graphene can lead to a significant reduction in production costs and the development of lighter and more compact devices without compromising performance. These advances not only enhance the efficiency of wireless communication systems but also open new possibilities for applications in challenging environments where durability and resistance to extreme conditions are crucial.

Despite the different characteristics and advantages that graphene presents as a promising material in the design of graphene-based antennas, there are also some limitations regarding the results and adaptation of the antenna in terms of axial ratio (AR). For example, in a study conducted by Upender (2024), it was found that for an antenna exhibiting resonance at two distinct frequency bands, namely 6.53 THz and 7.52 THz, the configuration of the full ground plane does not establish a strong coupling between the microstrip feed and the stacked dielectric resonator (DRs). As a result, the generation of circular polarization is hindered, leading to the observed limitations in AR performance and not providing a wide impedance bandwidth.

Also, in a study conducted by Sa’don *et al.* (2024), it is noted that most of the antennas designed and researched for 5G applications operate in the microwave (3 GHz to 30 GHz) and millimeter-wave frequency ranges. Many studies highlight their flexibility (Leng *et al.*, 2016; Secor *et al.*, 2013; Subbaraman *et al.*, 2013), ease of production compared to conventional materials (Kim *et al.*, 2013), and low cost (Huang *et al.*, 2015b). However, challenges in the design of these antennas are still being investigated, particularly regarding the tunable characteristics provided by graphene properties in these frequency bands, although the results show limited influence on resonance frequency and return loss.

From the above, the following research question was posed: What scientific advances have been made in the use of graphene in antennas for wireless communication applications? Therefore, to identify research trends in this area, this literature review adopted the PRISMA statement. To this end, the following research questions were addressed.

(i) RQ1: What are the years in which there has been the most interest in wireless communications systems designs using graphene?
(ii) RQ2: What type of growth occurs in the number of scientific articles on wireless communications systems designs using graphene?
(iii) RQ3: What are the main research references for the wireless communications systems designs using graphene?
(iv) RQ4: What are the main thematic clusters for the wireless communications systems designs using graphene?

2. METHODS

Literature reviews are used to assess the current status and scientific progress of a particular field of knowledge. This methodology is based on the selection, identification, and analysis of different studies that can guide and answer a research question (Pineda & Urrego, 2023). Different approaches to this methodology have been used over the years (Crowe & Sheppard, 2011; Lame, 2019), which include the following stages:

(i) Identifying the search strategy: In this stage, the authors define the database for conducting the literature search. In this study, we employed Scopus because it indexes literature in all areas of communication at the international level.

(ii) Defining the search strategy: In this stage, the search terms are selected. In this study, we used graphene, antennas, and wireless communications.

(iii) Reporting and interpreting the results using tables, charts, and summaries.

After completing the stages above, we established a suitable time frame, which meets the requirements of a literature review as indicated in (Cañas-mejía *et al*., 2023). Considering the above, we used Search String in the Scopus database.

TITLE-ABS (graphene AND antenna AND “wireless communications”)

This search string retrieved 168 articles directly related to the topic of “graphene and wireless communications.” Our search was restricted to documents published from 2012 to 2023, this is because, in previous years, the graphene research did not specifically address its application in antenna design but only mentioned the material without delving further into the topic.

The documents were included in this review only if their abstract showed a direct relationship with the topic addressed here. After this abstract analysis, we identified 14 especially relevant articles that would allow us to further analyze the literature in this field. Mendeley software was used to manage the bibliography, references, and citations. For this purpose, the downloadable version of the software was used to manage, share, and discover content and contacts in the research (Singh, 2010; Tian *et al*., 2024). It was also used for the automatic extraction of document details (authors, title, journal, etc.) and to enable the search for specific aspects and variables in the selected articles, allowing the creation of a database of these articles.

In addition, VOSviewer software was employed to analyze the database generated by Scopus. VOS Viewer is a specialized software application designed for visualizing and analyzing bibliographic networks in bibliometric research (Davin Arkan Admoko *et al*., 2024). The compilation process included all keywords, both from authors and indexing. To prevent the overlap of less significant qualities, a minimum of 5 occurrences per term was set, ensuring a clearer definition of thematic clusters. For author collaboration, a minimum of 2 authors per cluster was required.

Previous studies provide detailed guidance on using VOS Viewer (Al Husaeni & Nandiyanto, 2021; Azizah *et al*., 2021). The data generated by VOS Viewer illustrated networks of synonymous terms that could be grouped. These groups consist of multiple elements/terms that indicate each group's theme. The thematic consistency varies among the groups in the dataset, meaning that each group may or may not share the same underlying themes (Davin Arkan Admoko *et al*., 2024). **Figure 1** illustrates this process, which is based on the PRISMA methodology.

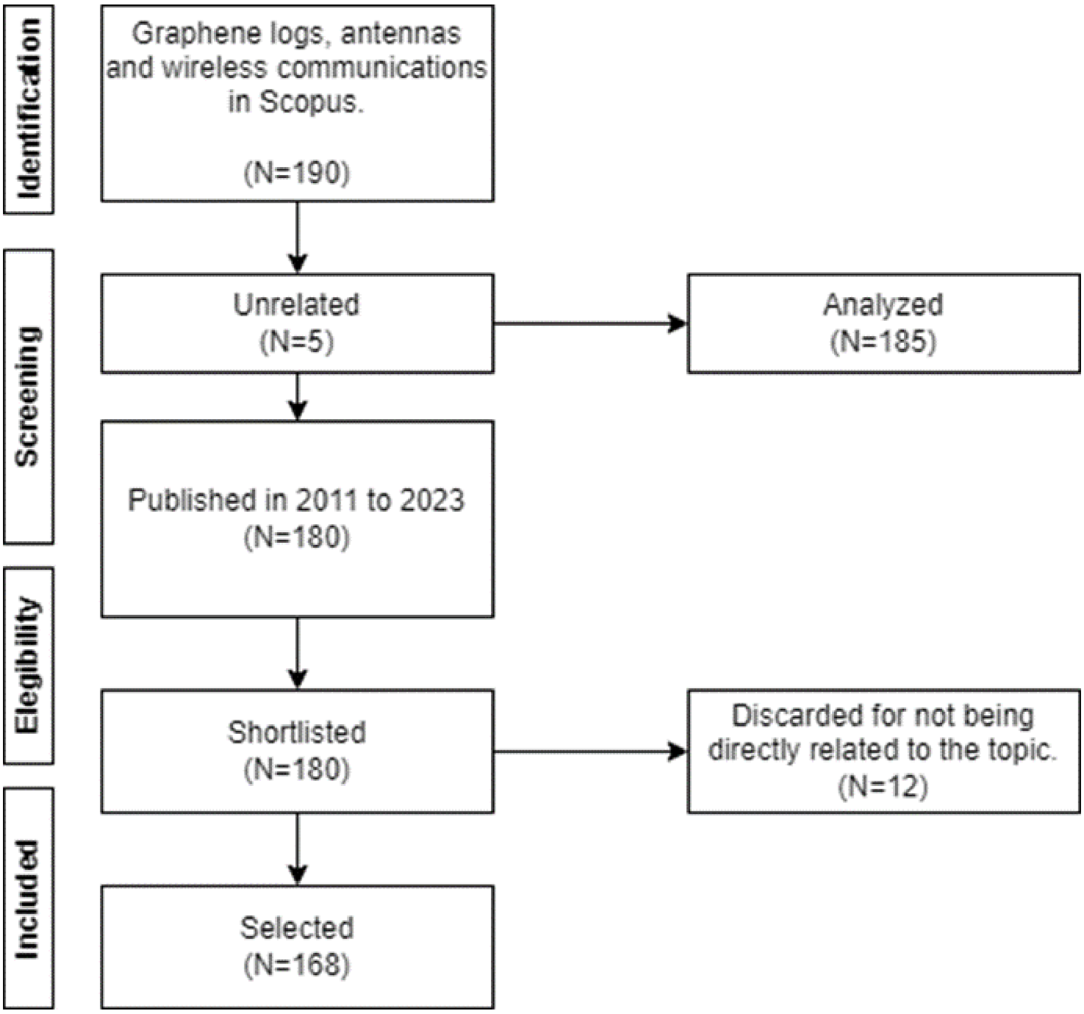

Figure 1. Flowchart of the PRISMA statement applied to this literature review. Source: Own work based on (Bravo-Linares *et al.*, 2019).

3. RESULTS AND DISCUSSION

3.1. Basic Concept

Graphene is a 2D metamaterial with a thickness equivalent to that of a single atomic layer. As a non-metallic material, it has outstanding electronic transmission characteristics (Sa'don *et al.*, 2020). The conductivity of graphene is complex, and its tuning properties appear when its chemical potential varies. As a 2D material made up of carbon atoms formed in a honeycomb lattice, graphene has the highest carrier mobility, i.e., 100,000 to 200,000 cm^2/V.S at room temperature (Sa'don *et al.*, 2020). These properties make it one of the top-performing materials for high-speed communications, even able to replace FR-4 and RT Duroid (in the case of microstrip antennas) (Kazemi & Mokhtari, 2017). Graphene's complex conductivity is expressed in Kubo's formula (σ), as shown in Equation (1):

$$\sigma(\omega,\mu_c,\tau,T) \approx -j\frac{e^2k_B\,T}{\pi h^2(\omega-j2\tau)} \times \left(\frac{\mu_c}{k_BT} + 2ln\left(exp^{\frac{\mu_c}{k_BT}}+1\right)\right) \tag{1}$$

where e is the elementary charge of the electron, k_B is the Boltzmann constant, T is the temperature, h is the reduced Planck's constant, ω is the radian frequency, and τ is the phenomenological scattering rate (Ullah *et al.*, 2020).

Graphene has potential applications in antennas (Kiani *et al.*, 2020), biosensors, filters (Kiani *et al.*, 2020), photodetectors (Khaouani *et al.*, 2021), modulators (Eslami *et al.*, 2021), waveguides (Shen *et al*., 2021), organic electronics, and devices operating in the terahertz band. This material has outstanding performance in the design of microstrip antennas because it favors miniaturization, easy integration into radio frequency (RF) systems, and mechanical flexibility (Bala & Marwaha, 2016). Graphene's properties improve antenna performance at the nanoscale operating in the terahertz band. Metallic antennas have a wave propagation speed of 2 x 10^8 m⁄s, while graphene antennas resonate in the optical electromagnetic domain (MacLeod & Rosei, 2014).

The discovery of graphene contributed to the development of modern communication systems, which rely on optical links that transmit data at the speed of light and on transmission and reception circuits that can encode substantial amounts of information in light beams (Ullah *et al*., 2020). Today, silicon is the best material for fabricating photonic waveguides in optical chips. Photodetectors are made of different semiconductors such as GaAs, InP, or GaN because silicon is transparent at standard telecommunication wavelengths. Nevertheless, integrating these semiconductors with silicon is difficult, which complicates fabrication processes and increases costs. Moreover, thermal management poses some additional challenges because photonic devices consume more power (Yan *et al*., 2021). Graphene-based integrated photonics is considered a key area for future development, with potential in high-speed optical networks that use less power than semiconductor photonics-based networks—keeping costs low and enabling integration with existing technologies.

3.2. Graphene Fabrication

Although graphene shares several properties with carbon nanotubes, it is commercially preferred because its fabrication is similar to that of silicon (Ando, 2009; Xia *et al*., 2017). Graphene devices are patterned using photolithography or electron beam lithography tools. Moreover, graphene is etched using oxygen plasma on metal components, and dielectrics are subsequently applied (Al-Mumen *et al*., 2014; Zhang *et al*., 2022). However, graphene fabrication poses four problems that still require optimization: substrate selection, contact resistance, gate dielectric deposition, and bandgap engineering. Every atom in a graphene film is located on the surface and strongly interacts with the environment, which offers numerous opportunities for new device concepts but also creates new sources of performance degradation. So far, the primary mechanism responsible for mobility degradation in graphene is charged impurities. Therefore, significant effort has been made to study various high-k dielectrics and substrates to mitigate the effects of charged impurities and surface phonons (Ma *et al*., 2020; Nag *et al*., 2018; Schwierz, 2013; Zhong *et al*., 2015).

Due to the growing interest in the use of graphene as a nanomaterial, two different chemical functionalization methods for obtaining graphene oxides (GO) are presented in Camargo Amado & Sevilla-Abarca (2021). The first method uses two strong acids (H_2SO_4 and HNO_3), while the second method employs three (H_2SO_4, HNO_3, and HCl). By SEM-EDS, FTIR, XRD, and Raman spectroscopy analysis, researchers were able to determine the presence of GO on the graphite plate surface. Furthermore, some researchers (Shams *et al*., 2015) followed an environmentally friendly method to obtain graphene from dead camphor leaves (Cinnamomum camphora) through pyrolysis. The method involved heating dead camphor leaves at 1200°C (10 °C/min). After cooling them to room temperature with D-tyrosine and centrifugation, they managed to separate some graphene layers (FLG) from the final pyrolytic components. They also employed Raman, SEM, AFM, and TEM to characterize the properties of graphene.

Another method, known as mechanical exfoliation, involves the use of adhesive tape or a simple peeling process to separate graphite layers and isolate graphene. Continuous peeling causes the graphene flakes to eventually separate from the tape (Wang *et al*., 2019). The tape is then bonded to a substrate, such as acetone, and passed multiple times to obtain flakes of various sizes and thicknesses. These flakes can be observed by optical microscopy over SiO_2/Si substrates (Correas-Serrano *et al*., 2015). The material produced is often reserved for study purposes rather than commercial applications (Edwards & Coleman, 2013). Other methods for obtaining graphene include extraction from crystalline SiC or transition metal substrates and chemical vapor deposition (CVD) of $CH_4OC_2H_2$ gases on copper or nickel substrates (Saha & Dutta, 2022).

The utilization of graphene printing and manufacturing methods for the design of antennas has led to advances in high-frequency applications, including focused aeronautical radio navigation. An example of this progress is the creation of a conductive layer in silk fabric by applying a conductive ink composed of graphene nanoparticles. The resulting surface resistance was 2.3 W/S and the conductivity was 0.435 x 10^5 S/m, with a focus on the 4200 MHz center frequency (Kumar *et al*., 2017b). Additionally, the researchers (Davis *et al*., 2023) used screen printing to design a surface coplanar antenna that incorporated a defective ground structure into an array component for improving radiation and gain. The results indicated that the graphene-printed antenna—composed of a single element—achieved a wide impedance bandwidth, a gain of 2.87 dBi, and an efficiency of 67.44%. Similarly, in another study, a graphene-based reconfigurable microstrip antenna was developed by printing a conductive ink composed of graphene nanoparticles on cotton. This antenna exhibited a surface resistance of 2.7 square feet, a conductivity of 0.37× 10^5 S/m, and a radiation efficiency greater than 55% in the dominant mode (TM 10) at a frequency of 3.03 GHz. Moreover, this antenna could switch between two frequency bands: the S-band at 3.03 GHz and the C-band at 5.17 and 6.13 GHz (Kumar *et al*., 2017a).

Graphene, being a two-dimensional material, presents a hexagonal network shape made up of carbon atoms that allow the production of thin substrate films for the construction of semiconductor elements, inductors, and transistors with optoelectric properties that they offer to systems. Communication devices operate at different wavelengths. The aforementioned qualities allow graphene to be a material that can be easily integrated into wireless communications systems since they allow these systems to work in a wide range of the electromagnetic spectrum, which may well be between 300 GHz and 10 THz (Hasan *et al*., 2016).

Antennas designed with graphene require low dispersion losses and high efficiency to support the propagation of electromagnetic waves in the GHz range [100] and even more. Thus, in the THz range, since the operating range increases, the device requires a smaller size due to the propagation of the waves that circulate through the structure. One of the main characteristics that influence these antennas is the geometry, because the circulation of the electrical flow through the surface of the material depends on it, giving rise to the resonance frequency, bandwidth, impedance, and radiation patterns (Dashti & Carey, 2018).

Now, to achieve the construction of efficient antennas and to work in the THz range, graphene due to its physical, chemical and mechanical characteristics allows the modeling of thinner and more compact antennas capable of tuning different resonance frequencies and configuring the input and output voltage generated by the electromagnetic waves and thus achieve different polarizations of the wave by concentrating or dissipating these waves, thus achieving different reconfigurations of the bands in the THz range. This is achieved by making slots within the proposed structure and parasitic elements can also be added that change the resonance configuration of the antenna (Kushwaha & Karuppanan, 2020b, Kushwaha & Karuppanan, 2020a).

3.3. Literature Analysis

Considering the results obtained and understanding the importance of graphene for the design of antennas for wireless communications, this review aims to establish the progress that has been made in this field of knowledge. Therefore, this review analyzed the quantity and quality of articles on graphene, antennas, and wireless communications. **Figure 2** shows the number of publications per year in this field, starting in 2012 when the first studies on this topic were published. For example, other researchers (Llatser *et al.*, 2012a) focused on designing a graphene-based nano-patch antenna for terahertz radiation, and it has garnered 340 citations in the Scopus database. **Figure 2** also illustrates that the number of publications grew steadily until 2021. Nevertheless, it slightly decreased from 22 in that year to 21 in 2022, which does not represent a significant difference. One of the most relevant publications in the field in 2021 was Gayduchenko *et al.* (2021), where tunnel field-effect transistors were harnessed for highly sensitive terahertz detection. The researchers capitalized on the tunable electric band structure of bilayer graphene (BLG), establishing a lateral tunnel junction that they linked to an antenna exposed to terahertz (THz) radiation. This publication has garnered 41 citations. Another impactful study in the domain is an exhaustive investigation of on-chip antennas. These antennas are based on principles of metamaterials, metasurfaces, and substrate-integrated waveguides tailored for millimeter-wave and terahertz integrated circuits and systems intended for wireless communication purposes (Alibakhshikenari *et al.*, 2022). This article has been cited 67 times to date.

Nevertheless, in 2023, a total of 18 documents addressing this subject have already been published, suggesting that this count is likely to increase throughout the year. One of the most influential studies in this arena, cited three times thus far, compared copper and graphene film assemblies in the context of 5G wireless communication and terahertz electromagnetic interference shielding. The study revealed that the array developed for 5G communication exhibited broader bandwidth and lower sidelobe levels than copper antennas (Song *et al.*, 2023).

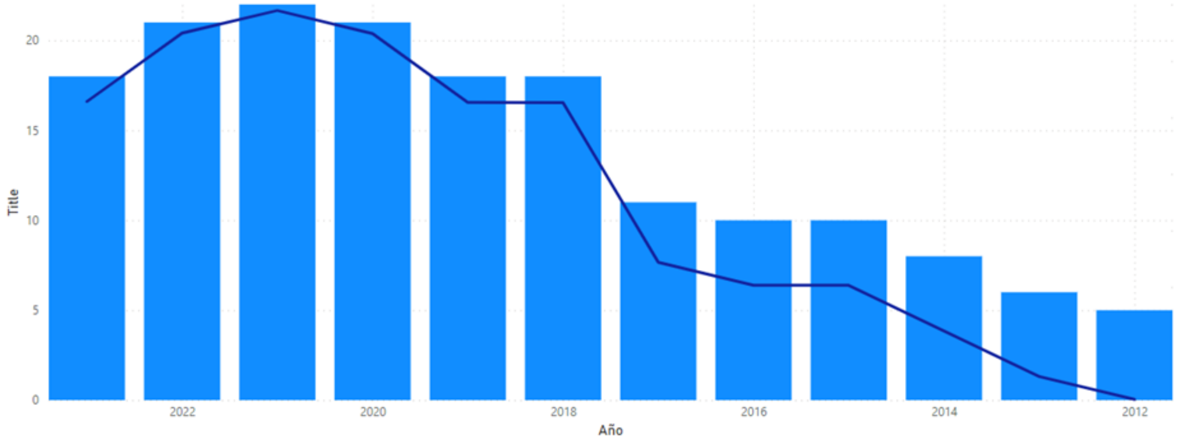

Figure 2. Publications per year.

Figure 3 lists the scientific journals with the most publications about graphene and wireless communications. Optik was found to be the leading periodical, with a total of six publications on this topic. One of the most relevant articles—with 126 citations in Scopus—addressed the simulation of a terahertz patch antenna based on graphene nanoribbons on a polyimide substrate and investigated its radiation emission in the 725–775 GHz band. It found that the antenna achieved a wide impedance bandwidth (>5%) in the operating band and a maximum gain of 5.71 dB at 750 GHz (Anand *et al.*, 2014). However, not all publications are related to design simulation; graphite monopole antennas have also been printed to operate in the GHz range, as in Song *et al.* (2023), where a graphene antenna was constructed to operate at the 2.4 GHz frequency. Similarly, printed substrates such as polyamide with graphene have been used for the construction of flexible antennas in the 867 MHz band for use in RFID systems (Arapov *et al*., 2016).

Current Nanoscience, Electronics, IEEE Access, and four other journals have three publications about graphene, antennas, and wireless communications. One of the most relevant articles published in these journals is a study that proposed a two-port graphene plasmonic Multiple Input Multiple Output (MIMO) microstrip patch antenna structure operating at a 1.9-THz resonance frequency. It was published in Electronics in 2023 and has been cited twice (Khaleel *et al*., 2022). In addition, one of the most impactful studies published in IEEE Access in 2022 (cited 67 times) is an extensive investigation of on-chip antennas employing metamaterial, metasurface, and substrate-integrated waveguide concepts for integrated circuits and systems operating in the millimeter-wave and terahertz frequency ranges (Eslami *et al*., 2021). Another widely cited document published in IEEE Access (39 citations) presents the design of a graphene-based multi-beam reconfigurable terahertz antenna (Luo *et al*., 2019).

Although Current Nanoscience is one of the most productive journals, its papers are not as highly cited as those in Electronics or IEEE Access. Nevertheless, one of its most cited papers (7 citations to date and published in 2016) explored the improvement of patch antenna performance in the terahertz region using graphene (Luo *et al*., 2019). Similar studies are relevant in this field because they lay the foundations to continue the search for different methods, tools, and processes to improve the quality of wireless communications. Other journals have also contributed to research in this area, but their productivity has not been very significant, with only one or two publications on the topic under study.

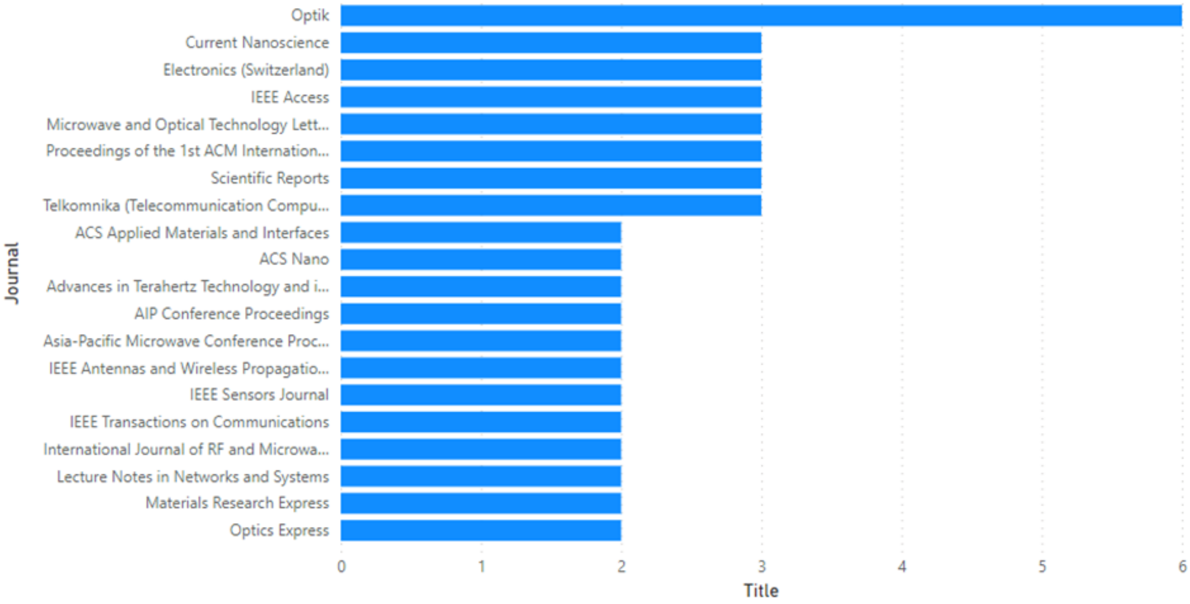

Figure 3. Most productive journals.

Figure 4 lists the most productive countries in this field. India has produced the highest number of publications on this topic, with 31 articles (13.03%). Among them, one of the most cited publications is a study on the development of a multifunctional smart textile made of nylon/merino wool polymer nanocomposites as a next-generation microwave absorber and soft touch sensor (Bansal *et al*., 2018). Another relevant paper from India addressed the creation of a patch antenna utilizing graphene on a glass substrate, intended for high-speed terahertz communication purposes (Mazo Vivar & Velasco Maillo, 2023).

In terms of productivity in the field of wireless communication antennas and graphene, the United States ranks second with 30 publications. A study from this country describes the fabrication of a 100 nm thin translucent MXene using an antenna with a reflection coefficient lower than -10 dB (Ghosh *et al*., 2020). China and the United Kingdom rank third and fourth with 21 and 20 publications, respectively. Two of the most outstanding publications from these two countries are (i) a study conducted in China on ultra-massive MIMO channel modeling for graphene-enabled terahertz-band communications (Sarycheva *et al*., 2018) and (ii) a comprehensive survey carried out in the United Kingdom on antennas utilizing metamaterial, metasurface, and substrate integrated waveguide principles designed for integrated circuits and systems that operate within the millimeter-wave and terahertz frequency ranges (Dashti & Carey, 2018).

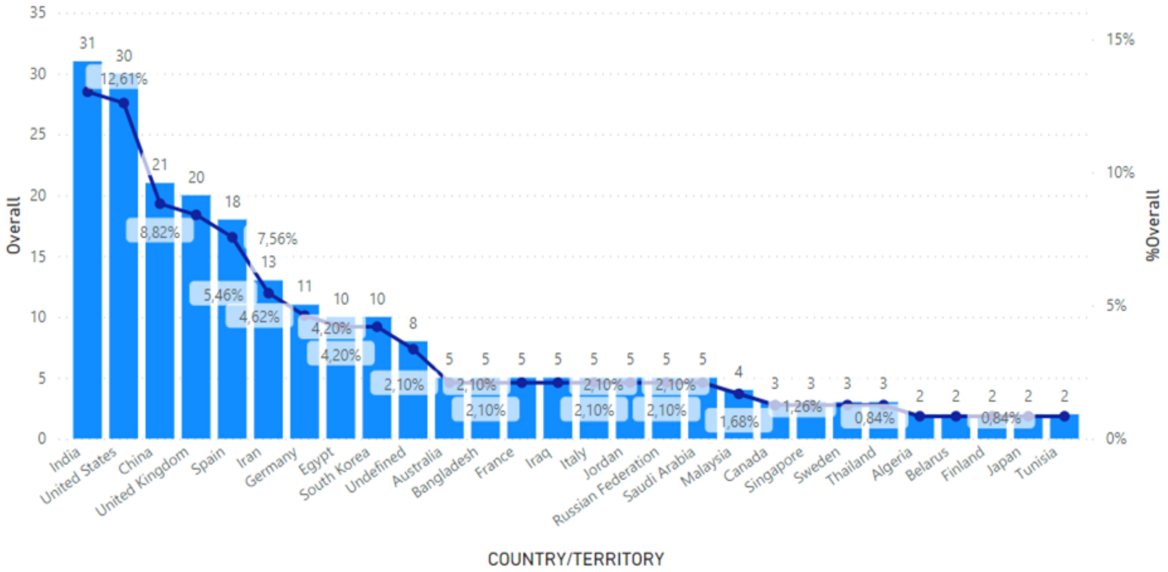

Figure 4. Most productive countries.

Figure 5 shows the co-authorship links among the most prominent researchers in this field based on the quantity and quality of their publications. The size of each circle is proportional to the number of publications produced. One of the strongest author networks in Figure 5 connects Cabellos-Aparicio, Llatser, Jornet, Alarcón, Kremers, and Chigrin, as evidenced by 14 publications and 11 links. In one of their most relevant publications, the authors designed a graphene-based nano-patch antenna for terahertz radiation (Llatser *et al*., 2012a). Another study by the same group addressed the fabrication of an antenna for ultra-massive MIMO (1024×1024) communication in the (0.06–10) terahertz band (Ghosh *et al*., 2020). Additionally, the same cluster conducted a study on graphene-enabled wireless communication for massive multicore architectures (Han *et al*., 2018a).

The second cluster in **Figure 5** comprises six authors, namely Abadal, Hosseininejad, Alarcon, Lee, Mestres, and Lemme. They have published a total of nine documents and established eleven co-authorship links. Some of their most relevant publications have dealt with the characterization of graphene-based nano-antennas in the terahertz band (Akyildiz & Jornet, 2016) and the use of terahertz photoconductive sources to characterize tunable graphene RF plasmonic antennas (Abadal *et al*., 2013). These two publications were written in collaboration with some of the authors in the first cluster.

The third cluster features Wang, Song, Zhang, He, Abadal, and Lemme—the last two were in the first cluster as well. This cluster represents three publications and five co-authorship links. In terms of citations, this cluster features three important sources: two papers (Cabellos-Aparicio *et al*., 2015; Llatser, 2012b) and an article that details the time-domain analysis of graphene-based miniaturized antennas for ultra-short-range impulse radio communications (Abadal *et al*., 2015). Moreover, in the fourth cluster, Hu, Pan, Zhou, and Leng have published together with Sogn and He.

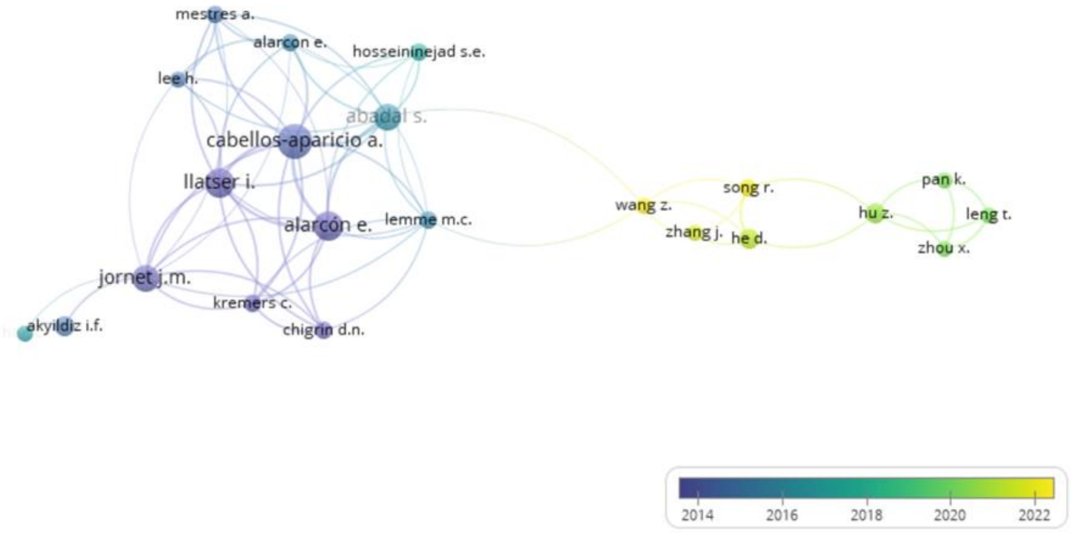

Figure 5. Co-authorship networks.

Figure 6 displays the yearly citation count of articles on the use of graphene for designing optical communication antennas. The highest number of citations corresponds to articles that were published in 2018, with a total of 571 citations. From this year onwards, there has been a decrease in citations on the topic concerning previous years. For instance, 2012 had a total of 541 citations, followed by 2013 with 467 citations, 2014 with 373 citations, and 2020 with 337 citations. These are the most representative years in terms of the quality of research in the area, considering the citation count. This could be attributed to the applications on which the articles focus. Although the topic emerged in 2012, it was not until 2018 that telecommunication applications gained importance due to novel technologies such as IoT.

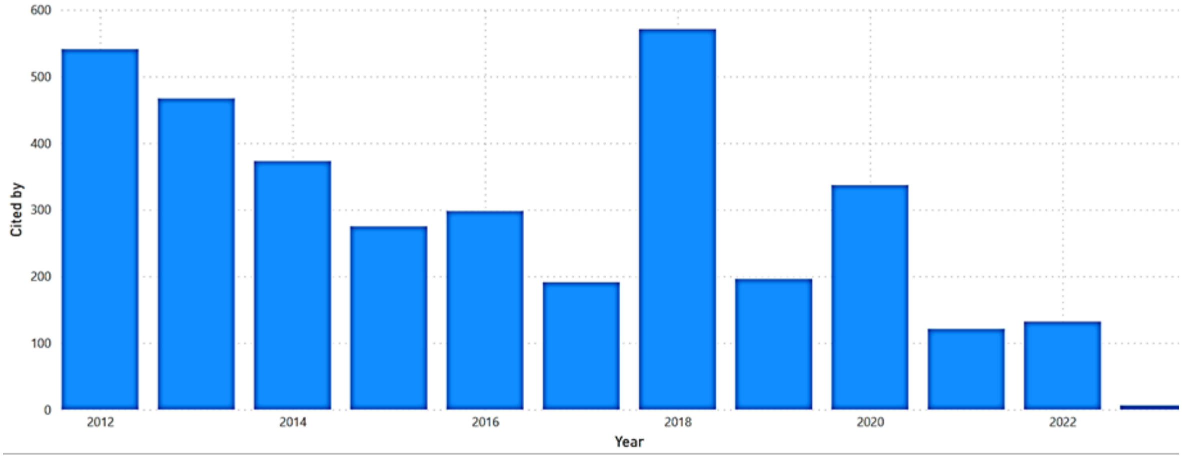

Figure 6. Article citation count by year of publication.

Regarding the most representative papers by year due to their citation count: from 2012, the paper titled “Graphene-based nano-patch antenna for terahertz radiation” Llatser *et al.* (2012a) has been cited 340 times. In 2013, the most cited article was “Graphene-based plasmonic nano-antenna for terahertz band communication in nanonetworks” Jornet & Akyildiz (2013), with 337 citations. From 2014, the article “Graphene nanoribbon-based terahertz antenna on polyimide substrate” has garnered 126 citations (Anand *et al.*, 2014). From 2015, the most cited article is “Wireless hydrogen smart sensor based on Pt/graphene-immobilized radio-frequency identification tag” by Lee *et al.* (2015) with 89 citations. In 2016, the study titled “Realizing ultra-massive MIMO (1024×1024) communication in the (0.06-10) Terahertz band” by Akyildiz & Jornet (2016) is the most cited with 181 citations.

Moreover, the article titled “Graphene-flakes printed wideband elliptical dipole antenna for low-cost wireless communications applications” by Sarycheva *et al.* (2018) is the most cited from those published in 2017, with 47 citations. In 2018, the paper “2D titanium carbide (MXene) for wireless communication” by Sarycheva *et al.* (2018) has been cited 306 times. From 2019, with 39 citations, the article “Graphene-based multi-beam reconfigurable THz antennas” by Luo *et al.* (2019) is the most cited. From 2020, which is the year with the most cited publications, the study titled “Smart, soft contact lens for wireless immune sensing of cortisol” Ku *et al.* (2020) has garnered 101 citations. In 2021, the article “Tunnel field-effect transistors for sensitive terahertz detection” Gayduchenko *et al.* (2021) is the one with the highest number of citations, with 41. As for 2022, the study titled “A comprehensive survey on on-chip antennas based on metamaterial, metasurface, and substrate integrated waveguide principles for millimeter-waves and terahertz integrated circuits and systems” Alibakhshikenari *et al.* (2022) has had a great impact, receiving 67 citations so far.

Table 1 shows the ten most cited articles among all those analyzed, providing an overview of relevant studies in the field of communications and nanotechnology, with an emphasis on wireless antennas and devices. For instance, a “graphene-based nano patch antenna for terahertz radiation” (2012) was introduced in 2012 and received significant attention, garnering 340 citations. This demonstrates the impact that graphene technology had on antenna research during that period.

In subsequent years, research continued to evolve. For example, the study titled "Graphene-based plasmonic nano-antenna for communications in the terahertz band" (2013) was published in 2013 and has received 337 citations. Similarly, "Titanium 2D MXene for wireless communication" (2018) was published in 2018 and has garnered 306 citations. These advances in antenna materials and techniques demonstrate the importance of developing more efficient and high-performance wireless communication technologies across a variety of frequency ranges.

In addition to antennas, **Table 1** mentions other innovative wireless devices, such as smart contact lenses for wireless cortisol immunosensing. These developments demonstrate the evolution of research in wireless communications and sensor technology to address a wide range of applications and challenges of modern society.

Table 1. Scopus' top-cited publications in the field of graphene, wireless communications, and antenna design.

Year	Title	Cited by	Reference
2012	Graphene-based nano-patch antenna for terahertz radiation	340	(Llatser *et al*., 2012a)
2013	Graphene-based plasmonic nano-antenna for terahertz band communication in nanonetworks	337	(Jornet & Akyildiz, 2013)
2018	2D titanium carbide (MXene) for wireless communication	306	(Sarycheva *et al*., 2018)
2016	Realizing Ultra-Massive MIMO (1024×1024) communication in the (0.06-10) Terahertz band	181	(Akyildiz & Jornet, 2016)
2014	Graphene nanoribbon-based terahertz antenna on polyimide substrate	126	(Song *et al*., 2023)
2013	Graphene-enabled wireless communication for massive multicore architectures	119	(Abadal *et al*., 2013)
2014	Graphene-based plasmonic nano-transceiver for terahertz band communication	105	(Jornet & Akyildiz, 2014)
2020	Smart, soft contact lens for wireless immunosensing of cortisol	101	(Ku *et al*., 2020)
2015	Wireless hydrogen smart sensor based on Pt/graphene-immobilized radio-frequency identification tag	89	(Lee *et al*., 2015)
2012	Radiation characteristics of tunable graphenes in the terahertz band	77	(Llatser, 2012c)

3.4. Discussion

The rapid evolution and development of telecommunications technologies have forced humanity to search for and develop new materials that are multifunctional, multipurpose, and that are compatible with various communications systems and electronic systems, in addition; that are low cost and compact. With the arrival of graphene, multiple applications have been found for this material, specifically in communications systems. The tunability, the range of frequencies in which this material can operate, and the compatibility it has with other materials allow countless designs and arrangements to be made. Antennas with different geometries and combinations of materials such as graphene with glass or graphene with copper and other types of metals.

Graphene is a material that allows modifying the design of antenna structures to improve their performance such as the bandwidth and gain of the antenna. This can be done by inserting slots in its structure; slots can also be made in the form of circular or rectangular rings, thus obtaining an antenna with a resonant structure. There are also other geometries such as fractal designs that, thanks to their shape inspired by nature, can be more efficient, smaller in size, and avoid unnecessary waste of material.

Microstrip antennas have emerged not only as antennas for communications systems but also as permittivity sensors, deformation sensors, and sensors used in the health area; Due to the characteristics of their high conductivity and sensitivity, graphene antennas lend themselves to making these sensors since they are more susceptible to changes in temperature and pressure and since they are capable of working at very high frequencies, this makes them have extreme sensitivity to obtain results more quickly and effectively in patch antenna-based sensor systems.

Graphene has exceptional optical, thermal, and electronic properties. In addition, it is bi-dimensional and easy to integrate. This makes it an attractive candidate for a new generation of high-performance devices that can improve the performance of communications technologies in the terahertz range (between 300 GHz and 10 THz) (Ullah *et al.*, 2020). In several studies, graphene has been used as the primary material to design antennas for different applications, e.g., sensors and microwave components. For instance, some researchers (Llatser *et al.*, 2012b) constructed a high-gain and ultrawide-band graphene patch antenna with photonic crystal covering 96.48% of the terahertz band. The antenna developed exhibited a −10 dB impedance bandwidth of 9.552 THz, operating within the range of 0.448 to 10 THz, encompassing approximately 96.48% of the entire terahertz communication spectrum. In addition to its remarkably wide bandwidth, the antenna showcased a maximum gain of 21.22 dB and a peak radiation efficiency of 93.23%.

In a different study (Khan *et al.*, 2021), researchers introduced a reconfigurable antenna incorporating a feed line and a graphene load. This modification led to a significant shift in the antenna's resonant frequency and a substantial gain increase of up to 4 dBi. The simulation in this document analyzed an adjustment and demonstrated a 78% increase in antenna efficiency, indicating more than a 100% improvement compared to the basic antenna. This improvement was achieved by increasing the graphene chemical potential. In another study Kushwaha and Karuppanan (2020a), researchers proposed a circular graphene microstrip patch antenna on a silicon substrate, featuring an optimized return loss of -26 dB, a -10 dB bandwidth of 504 GHz, and an antenna efficiency of -3.4 dB at a frequency of 2 THz. An even better antenna efficiency of -0.36 dB was achieved at 3.5 THz, offering a bandwidth of approximately 200 GHz. These substantial bandwidths and high antenna efficiencies hold promise for creating flexible graphene-based directional antennas suitable for future terahertz local device-to-device communications.

Furthermore, some researchers Gayduchenko *et al.* (2021) presented a novel dual-band miniaturized antenna array utilizing graphene and employing parasitic-coupled feed. This array was mounted on a PBG (Photonic Bandgap) dielectric grating substrate designed to operate within the frequency range of 0.85 to 1.04 THz. The design showcased remarkable features such as a minimum return loss of -52.58 dB, a VSWR of 1.005, an impedance bandwidth of 33.34 GHz, a peak gain of 16.4 dB, and a peak directivity of 17 dBi. The utilization of the parasitic-coupled approach simplified the antenna array’s complexity, making it suitable for imaging, spectroscopic security, and wireless communication applications. Some researchers (Alibakhshikenari *et al.*, 2022) used photonic crystals and dielectric grating to design a graphene-based patch antenna array with ring resonators for THz applications. The frequency range was from 0.84 to 0.94 THz. The researchers achieved a peak gain of 14.69 dB and a directivity of 15.5 dBi.

Graphene antennas provide excellent parameters such as gain, bandwidth, and directivity for use in the terahertz range. However, given the complexity of the geometry, designing these antennas requires methods such as neural networks to achieve an optimal design without incurring excessive costs (Seyedsharbaty & Sadeghzadeh, 2017). To address these design challenges, printing techniques, such as screen-printing with graphene-compatible inks and substrates, have been employed. For example, Kapton polyimide films are used as templates for spreading graphite with a spatula to create the required geometry for printing. This technique is less expensive and has proven successful in designing graphene antennas for 5G applications (Mashayekhi *et al.*, 2023).

Graphene antennas are often designed to operate in the terahertz range due to their size on the nanometer scale. However, liquid-phase exfoliated graphene sheets can also be used for printing electronics. Specifically, some researchers (Llatser *et al.*, 2012c) described a high-performance printed 2.4 GHz graphene-based antenna. Graphene conductive ink prepared by using a liquid-phase exfoliation process was printed on a water-transferable paper by using a blade printing technique, which was then modeled as a dipole antenna and transferred to a substrate. The manufactured antenna (43 × 3 mm) showed radiation patterns typical of an ideal dipole antenna, as well as a −10 dB bandwidth of 8.9% with a maximum gain of 0.7 dBi. The graphene antennas met the application requirements of the IoT and suggested replacing conventional metal antennas in those applications.

Most of the frequency spectra used in the design of graphene antennas are in the millimeter-wave category. This spectrum overcomes the bandwidth limitations and congestion that occur in antennas made of conductive materials such as copper. However, at the high-frequency spectrum, the demand for greater capacity can be met by the large bandwidth produced by graphene. Therefore, the high data rate service should reach up to 1 Gb/s, with an omnidirectional radiation pattern and a gain between −8 and 0 dBi, as indicated in Mashayekhi *et al.* (2023).

Moreover, recent studies have explored innovative designs for terahertz applications. For instance, some researchers (Sa'don *et al.*, 2019) developed and evaluated a graphene antenna consisting of a graphene dipole and four auxiliary graphene sheets that act as reflectors, as they are arranged perpendicularly to each other. The operation of this proposed antenna covers a frequency range of 1.75 to 2.03 THz and achieves a maximum gain that varies between 0.86 and 1.63, depending on the active regime defined by the chemical potentials applied to the graphene components.

In another study described by Dmitriev *et al.* (2023), a dual-band graphene coplanar waveguide antenna was designed for smart cities and IoT applications. To build this antenna, a graphene film was used as the conductive material for the radiation patches, and the ground plane was made of glass with a thickness of 240 µm and an electrical conductivity of 3.5×10^5 S/m. In addition, glass was used as the dielectric, which had a dielectric permittivity of 6 and a thickness of 2 mm. This design managed to cover two frequency bands: the lower band that covered the 2.45 GHz ISM frequency and the upper band that extended from 4 GHz to 7 GHz.

Figure 7 shows the network of keywords and links among studies. They represent the topics that have been discussed in this review, especially the applications, materials, and elements that have been considered in the design and construction of graphene-based antennas. The keywords in teal circles emerged approximately in 2018—they compose the first cluster in Figure 6. In that year, the most common term in the selected studies was *graphene*. One of those studies (Morales-Centla *et al.*, 2022) investigated a metallic antenna backed by a graphene-based reflector. The term graphene was also used in combination with other keywords, e.g., graphene-based antenna and graphene antenna. This term has also been used for wearable antennas. For instance, in Tang *et al.* (2017), a hybrid terahertz antenna was designed for body-centric applications. Other researchers (Abohmra *et al.*, 2019) proposed different designs for flexible and wearable antennas that can be used in applications that do not affect human health and portable devices.

The second cluster in **Figure 6** revolves around the keyword *terahertz*, which refers to the operating frequency for which graphene is generally used in antenna design. Several publications that feature this term also contain other keywords, i.e., flexible, miniaturized, tunable, and conductivity, which were more commonly used in 2017. Usually, the articles where these terms appear present smaller designs in terms of geometry and flexible materials. This enables antennas to be more easily tailored for specific applications and improves their conductivity and propagation performance (Abohmra *et al.*, 2019).

The third cluster (mostly purple circles) comprises the keywords *nano-antenna*, *plasmonics*, *nanonetworks*, *graphene*, and *graphene-based antennas*. Nano-antennas are designed in the nanometer scale to send and transmit electromagnetic waves (Inum *et al.*, 2016). This is in line with the miniaturized antennas that appear in other clusters. In this cluster, some studies have explored nanomaterials such as graphene, carbon nanotubes, metallic nanomaterials, and metamaterials in wideband millimeter-wave nano-antennas to meet the antenna requirements of 5G networks (Lalu & Anujan, 2023).

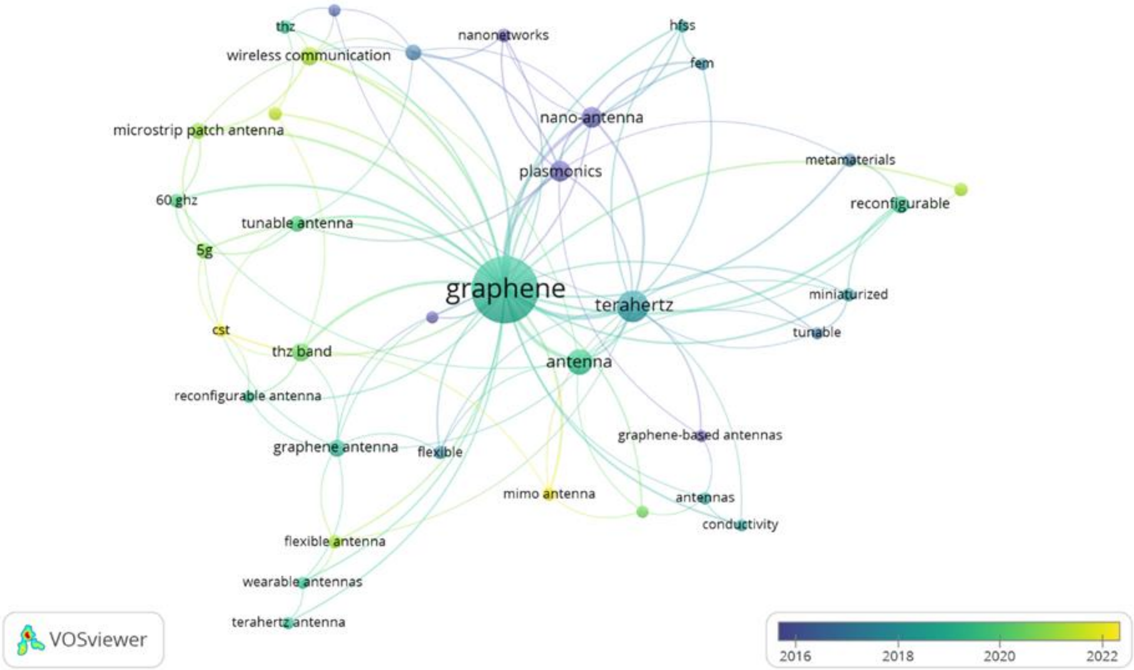

Figure 7. Keyword co-occurrence network.

The other clusters in this figure include keywords such as *wireless communication*, *microstrip patch antenna*, *5G*, and *antenna array*. More recent publications have focused on 5G communications and microstrip patch antennas. In a recent study employing these concepts, researchers introduced a high-gain 1 × 2 microstrip patch antenna array. This array was designed using both periodic and non-periodic photonic crystals, and it incorporated a graphene load. The primary objective was to enable operation within the terahertz (THz) frequency band, which holds significance in various fields such as sensing, imaging, and wireless communication technologies. Another study by Benlakehal *et al.* (2023) sought to design and analyze various antenna and antenna array configurations across the whole THz range by integrating graphene material into various patch and feedline combinations for a single antenna.

The keywords *CST* (which refers to a software package for simulating electromagnetic components and systems) (El Hassani & Saadi, 2023) and *MIMO antenna* appeared fewer times in the selected documents. Recent publications have examined several configurations of graphene-based MIMO antennas for different applications (Llatser *et al*., 2012). MIMO antennas are based on multicarrier modulation to favor mm-wave communication and, mainly, terahertz communication. Finally, the search string was adjusted to retrieve documents that exclusively addressed graphene's use in the design of wireless communication antennas. As a result, the search retrieved 14 documents. **Table 2** details the applications, materials, bands, and systems described in the sources.

Table 2. Main factors associated with the use of graphene in wireless communication

N°	Year of publication	System	Material (conductor/ substrate)	Band	Application	Reference
1	2023	Antenna array	Gold and graphene	Terahertz	Wearable devices	(Bharathi *et al.*, 2021)
2	2022	MIMO antenna	Graphene and polyimide	Terahertz	Wireless communication	(Abohmra *et al.*, 2023)
3	2021	Quasi Yagi–Uda antenna array	Graphene (substrate integrated waveguide)	Terahertz	6G communication	(Alharbi & Sorathiya, 2022)
4	2021	Slot antenna	Poly (3,4-ethylene dioxythiophene) (PEDOT) and N-doped reduced graphene oxide (N-doped rGO)	Terahertz	Wireless communication	(Tabatabaeian, 2021)
5	2021	2×1 CPW ultra-wideband rectangular slot antenna array	Rogers RO4003 substrate and graphene	Gigahertz	Wireless communication	(Thanh Tung *et al.*, 2021)
6	2021	MIMO antenna	Graphene	Gigahertz	5G communication	(Elsheakh & Dardeer, 2021)
7	2021	CPW 1×2 planar array antenna	Graphene	Gigahertz	5G communication	(Song *et al.*, 2021)
8	2020	CPW linear array antenna	Graphene	Gigahertz	Portable devices	(Zhou *et al.*, 2021)
9	2019	CPW monopole antenna	Graphene	Gigahertz	Wireless communication	(Zhou *et al.*, 2020)
10	2018	Patch antenna	Graphene and graphene-copper	Terahertz	Wide-band applications	(Pan *et al.*, 2019)
11	2019	Nano-patch antenna	Graphene - silicon dioxide (SiO2)	Gigahertz	Wireless communication	(Wang *et al.*, 2019)
12	2017	Patch antenna	Graphene	Terahertz	Wireless communication	(Mobarok Shamim & Iqbal, 2017)
13	2017	Screen-printed wideband elliptical dipole antenna - CPW	Graphene - Kapton	Gigahertz	Low-cost wearable devices	(Cabellos-Aparicio *et al.*, 2015)
14	2013	Nano-patch antenna	Graphene	Terahertz	Wireless communication and wireless power transfer	(Sirisha Mrunalini & Arun, 2016)

Table 2 indicates that GHz and THz are the two most common bands for which graphene is used as a conductor in the design of wireless communication antennas. In addition, it shows that recent studies have used MIMO antennas for next-generation network applications, i.e., 5G and 6G.

Additionally, some of the specific parameters regarding gain, antenna efficiency, operating frequencies, configuration, geometry, substrate, and other technical details specific to the advancements in antenna design using graphene can be described as follows:

(i) Microwave Slot Antenna Configuration. Substrate: 4-inch high-resistivity Si wafer with a 300 nm SiO2 layer grown via thermal oxidation. Graphene Layer: CVD is grown and transferred onto the SiO2 layer. Antenna Structure: Fabricated in coplanar waveguide topology with a rectangular graphene patch separated by a slot from the rest of the circuit, which is made from gold. Outer gold electrodes are grounded while the central electrode is excited by the microwave signal. Dimensions: Slot widths are 350 μm (x-axis) and 600 μm (y-axis). The thickness of the dielectric substrate is 500 μm (Dragoman *et al.*, 2015).

(ii) Operating Frequency and Bandwidth. Frequency Range: The antenna operates in the X band (8^{-12} GHz). Reflection Parameter (S11): Shows tunable behavior with DC voltage, with resonances at 8.8 and 11.4 GHz. Reflection loss is about -9 dB, with minimum values of -12.2 and -13.4 dB at 0 V applied DC bias. Wideband Nature: The graphene antenna is wideband compared to metal antennas of the same geometry, which are narrowband (Dragoman *et al.*, 2015).

(iii) Gain and Efficiency. Simulated Gain: Approximately -8 dB without backside metallization and -6 dB with backside metallization at 10 GHz. Radiation Efficiency: Lower than that of metallic antennas but can be improved by optimizing the technological process and antenna topology, including the graphene DC bias configuration. Beamwidth: 3 dB beamwidth between 40° and 80° for the radiation patterns, with no side lobes at 7 GHz and one side lobe at 12 GHz when using backside metallization (Llatser *et al.*, 2012a).

(iv) Tunable Graphene Antenna Array. Graphene Conductivity Variation: Conductivity of about 10 S/m with 20 V bias and 1000 S/m at zero voltage. Impedance Model: Equivalent circuit model with impedance Rg and inductor Lg in series. The surface impedance Zs and conductivity σ are dependent on the applied voltage, enhancing tunability. Reconfigurable Operation: By adjusting the DC voltage applied to the graphene sheet, the operating frequency and maximum gain can be electronically tuned (Llatser *et al.*, 2012a).

(v) Circular Patch-Shaped Yagi-like MIMO Antenna. Material and Dimensions: Graphene with a thickness of 0.03 μm and conductivity of 10^8 S/m. The overall size is $620 \times 800\ \mu m^2$, with a polyamide substrate thickness of 16 μm and a dielectric constant of 4.3. Design and Performance: Simulated for a resonating frequency of 7.5 THz, showing variation in S parameters and operating bands with accepted return loss. Three operating bands were observed across different port excitations (Llatser *et al.*, 2012a).

(vi) Plasmonic Dipoles and Patch Antennas. Graphene Dipole Characteristics: Input impedance and resonant frequency heavily rely on full-wave simulations. The capacitance between dipole arms and reactance at terminations are critical factors. Performance Metrics: Radiation efficiency and total efficiency vary with chemical potential. Miniaturization is achieved by exploiting the high inductance of graphene (Dragoman *et al.*, 2015).

Parametric Study and Simulation. Surface Plasmon Polaritons (SPP): Propagation modeled using Kubo formalism, focusing on chemical potential and relaxation time influences on graphene conductivity. Design Guidelines: Guidelines are provided for optimizing radiation performance by selecting appropriate graphene conductivity parameters (Llatser *et al.*, 2012a).

Graphene-based microstrip antennas represent a significant advancement in the field of wireless communications. These antennas leverage the unique properties of graphene, including high conductivity, tunability, and flexibility, to achieve superior performance metrics such as wide bandwidth, tunable operating frequencies, and miniaturization. Research has demonstrated the feasibility of using graphene for a variety of antenna designs, including microwave slot antennas, circular patch-shaped Yagi-like MIMO antennas, and plasmonic dipoles. These designs exhibit notable characteristics such as wideband performance, tunability via DC bias, and enhanced radiation efficiency. The integration of graphene into antenna design paves the way for innovative applications in high-frequency communications, particularly in the terahertz and microwave bands. Furthermore, taking into account the research keywords, the following research trends, opportunities for future research, and research gaps were identified.

3.5. Research Trends

In the field of wireless communications, there is a significant interest in studying antenna systems in matrix configurations (antenna arrays) and MIMO technologies. This field remains highly relevant and is characterized by the exploration of graphene applications for improving the performance of antennas in MIMO systems. The possibility of designing antenna array formations using graphene for specific applications is also being investigated. Furthermore, research on Quasi Yagi-Uda antennas focuses on optimizing their structures for wireless communication applications. This could involve incorporating advanced materials such as graphene into the design process to enhance their performance.

In the case of slot antennas, which are known for their slim profile and wide bandwidth, researchers are actively exploring how graphene can improve both efficiency and performance, especially in contexts that demand wide bandwidths. Rectangular slot antennas with CPW (coplanar waveguide) technology and their application in array configurations (e.g., CPW ultra-wideband rectangular slot antenna array) are relevant for broadband applications. In this sense, research focuses on designing and optimizing antennas by integrating graphene to achieve even wider bandwidths and improved overall performance.

Array antennas and linear arrays based on CPW technology (e.g., CPW planar array antenna and CPW linear array antenna) are key components in wireless communications systems. Researchers are focusing their efforts on incorporating graphene into these structures to improve efficiency, directivity, and bandwidth. Meanwhile, monopole antennas with CPW technology (CPW monopole antenna) are widely used in communication applications, and research in this area aims to enhance these antennas by incorporating graphene to achieve higher efficiency and better impedance matching.

Similarly, patch antennas and nano-patch antennas play a leading role in wireless communications. Current research is therefore focused on employing graphene to enhance antennas' performance, including the potential for miniaturization and transmission efficiency. Screen-printed elliptical dipole antennas with CPW technology (screen-printed wideband elliptical dipole antenna - CPW) are well-known for their affordability and versatility. Consequently, studies aim to print these antennas using display technology and integrate graphene for wider bandwidth and improved performance.

3.6. Opportunities for Further Research

Based on the results of the literature review, we propose some future lines of research on the use of graphene for designing wireless communication antennas:

(i) Characterization of electromagnetic properties of advanced materials: One possible line of research is a more in-depth characterization of the electromagnetic properties of advanced materials such as graphene and polyimide. This involves a comprehensive analysis of their electrical conductivity and dispersion of electromagnetic waves, as well as their versatility for various applications in different frequency bands. These studies are critical to understanding how these materials can improve the performance of antennas in specific contexts.

(ii) Terahertz communications and terahertz antennas: The terahertz spectrum has generated considerable interest for its high-speed potential in short-range communications. As a result, research focuses on the design and development of terahertz antennas that make efficient use of materials such as graphene. Optimizing these antennas is essential for the evolution of this technology.

(iii) Quasi Yagi-Uda antennas for 6G communications: The evolution towards 6G communication presents an exciting research opportunity in the field of graphene-based Quasi Yagi-Uda antennas. This approach involves adapting and optimizing these antennas to meet the rigorous performance requirements of 6G applications, which are expected to be highly advanced and demanding in terms of bandwidth and transmission speed.

(iv) Gigahertz MIMO antennas for 5G communications: In the context of 5G and future communication technologies, graphene-based MIMO antennas operating in gigahertz frequency bands play a crucial role. Further research could focus on improving the efficiency and capacity of these antennas to meet the increasing demand for high-speed connectivity in 5G and subsequent networks.

(v) Antennas for portable and affordable devices: Graphene antennas on affordable substrates, such as Kapton, provide research opportunities for developing antennas adapted to low-cost portable devices. Further research could explore manufacturing methods to optimize these antennas for use in the constantly expanding market of next-generation wearable devices.

(vi) Nano-antennas and nanoscale applications: The attention given to nano-antennas, especially those based on graphene, is an exciting opportunity for research in wireless communication and wireless power transfer. These nano-antennas can be essential for IoT and remote sensing applications. Therefore, studying their design, performance, and potential applications is imperative.

(vii) Optimization of high-frequency broadband antennas: Wideband antennas, such as ultra-wide rectangular slot antennas, pose an interesting challenge. Future lines of research could focus on optimizing these antennas for superior performance in high-frequency and high-speed applications, which is key to ensuring effective connectivity in high-demand communication environments.

(viii) Integration of wireless communications and power transfer: Nano-patch antennas represent a promising area of research for integrating wireless communication and wireless power transfer technologies. Further research in this field could lead to innovative developments and positively impact the efficiency and sustainability of wireless networks.

3.7. Research Gaps

In this way, they highlight the various applications that graphene can have in various contexts. Mainly in the area of telecommunications, considering properties such as; the electrical conductivity of graphene can be enhanced as the number of printed graphene layers increases (Pierantoni *et al.*, 2013). As the conductivity of multilayer graphene sheets increases, they perform effectively as microwave antennas, offering high gain when compared to copper (Elmobarak *et al.*, 2017).

For instance, a frequency-reconfigurable antenna with a monopole radiation pattern based on a graphene substrate structure was utilized (Pierantoni *et al.*, 2013). This configuration achieved a reconfigurable radiation pattern and frequency storage capability, effectively collecting a significant amount of radiofrequency energy. It covered a wide range of bands, from 3 GHz to 7.5 GHz, encompassing 5G and 4G bands, with an omnidirectional radiation pattern (Naghdehforushha & Moradi, 2018). The antenna achieved an average gain of approximately 1.8 dBi and a radiation efficiency of around 75% across the operating bands (Elsheakh, 2019). Consequently, advanced carbon-based conductive films, particularly graphene films, exhibit more advantageous properties than traditional metals in terms of flexibility, mechanical reliability, and weight savings (Tang *et al*., 2018). This holds significant potential for flexible electronic devices, especially in applications related to RF energy detection. In addition to representing an opportunity for the design of next-generation communications systems, due to the flexibility of adaptation, high speeds, and reconfiguration capacity, as mentioned in García-Pineda *et al*. (2023), where the integration of this type of material for applications in mobile networks under the integration of machine learning (see **Table 3**).

Table 3. Research gaps: Compiled from Scopus.

Gap Type	Research Gap	Purpose	Questions for Future Researchers
Thematic Gaps	1. Characterization of electromagnetic properties of advanced materials	Explore how graphene and other advanced materials affect electromagnetic properties.	What are the key electromagnetic properties that graphene can improve in antennas?
	2. Terahertz communications and terahertz antennas	Investigate how graphene can optimize performance in the terahertz band.	How can graphene improve the efficiency of terahertz antennas?
	3. Quasi Yagi-Uda antennas for 6G communications	Analyze how graphene-based antennas can contribute to 6G networks.	What benefits can graphene-based Quasi Yagi-Uda antennas bring to 6G communications?
	4. Gigahertz MIMO antennas for 5G communications	Investigate how graphene can improve the efficiency and capacity of gigahertz MIMO antennas.	How can graphene increase the capacity of MIMO antennas in 5G networks?
	5. Antennas for portable and affordable devices	Explore how graphene can enable cost-effective antennas for wearable devices.	How can graphene contribute to the design of affordable antennas for mobile devices?
	6. Nano-antennas and nanoscale applications	Investigate the applications of graphene-based nano-antennas in communications and nanometer-scale sensors.	What are the revolutionary applications of graphene nano-antennas?
	7. Optimization of high-frequency broadband antennas	Study how the performance of broadband antennas at high frequencies can be optimized.	How can graphene be used to achieve optimal performance in broadband antennas at high frequencies?
	8. Integration of wireless communications and power transfer	Investigate how graphene can improve the convergence of wireless communications and power transfer.	How can graphene facilitate the integration of wireless communications and wireless charging?
Geographic Gaps	Regional	Study the adoption of graphene in antennas across different geographical regions and its implications.	How does the implementation of graphene in antennas vary by geographic region?

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Table 3 (continue). Research gaps: Compiled from Scopus.

Gap Type	Research Gap	Purpose	Questions for Future Researchers
Interdisciplinary Gaps	Materials science	Explore collaborations between material experts and antenna experts to optimize the use of graphene.	How can material scientists and antenna engineers work together effectively?
Temporal Gaps	1. Historical	Analyze the historical evolution of the use of graphene in wireless antennas and its impact on technology.	How has the use of graphene in antennas evolved?
	2. Futuristic	Explore future trends in the use of graphene in antennas and its potential applications in the future.	What are the prospects and applications of graphene in antennas and wireless communications?

3.8. Limitations

While these bibliometric studies have significantly contributed to understanding Wireless Communications using Graphene, it is crucial to acknowledge some limitations in their approach and scope. Firstly, this research relies on the compilation and analysis of data available from Scopus, which could introduce bias in the selection of included publications. Additionally, the PRISMA-2020 methodology, though widely accepted and utilized in scientific literature, has its limitations regarding the inclusion or exclusion of certain studies.

Another potential limitation concerns the tools used for the bibliometric analysis. Although Microsoft Excel® and VOSviewer® are well-regarded and frequently used in the scientific community, their application can be subject to human error during data collection and processing, as well as technical constraints in result interpretation. Moreover, the bibliometric metrics employed to evaluate the quantity, quality, and structure of publications may not entirely capture the impact and relevance of studies in the fields of Wireless Communications and Graphene.

Finally, it is essential to recognize that these bibliometric analyses primarily focus on thematic evolution, keyword co-occurrence networks, and the identification of emerging and growing concepts. While these aspects provide a valuable overview of research trends, they do not comprehensively address other critical factors such as the methodologies employed, technical limitations, and practical applications of the studies. Therefore, additional research is needed to complement these bibliometric analyses by exploring more specific and detailed aspects of the relationship between Wireless Communications and Graphene.

4. CONCLUSION

Research interest in graphene for wireless communication is growing as evident from the steady rise in publications on this topic from 2012 to 2021. Although 2022 showed a slight decrease (one publication less), the trend for 2023 is once again upward. The journal that has published the highest number of papers in this area is Optik, which is due to the nature of wireless communications. It is followed by journals focused on nanoscience because of the relationship between graphene and the miniaturization of patch antenna design, as well as the nature of graphene as a promising material in nanoscience and nanocomputer design. Other journals that have addressed this topic are found in various engineering fields, mainly focusing on telecommunications and electronics. India has published the highest number of documents on graphene for wireless communications, followed by the USA. This is directly related to the network of authors who have worked in this area, as most of them are located in India and the USA, thus forming strong research clusters.

Finally, based on their keywords, most studies reviewed here have mainly investigated graphene and antennas for next-generation communications. More specifically, they have explored applications for the terahertz band and found that ultrawide-band applications can better respond to the demand for network resources that 5G and 6G networks bring in the future, due to the massive number of devices that will be connected to the internet (i.e., the IoT). Further research could delve into the use of graphene in cost-effective applications compatible with 5G and 6G technologies. Furthermore, MIMO technologies can work better in the design of graphene-based antennas in the THz band. Magna. *Pellentesque habitant morbi tristique senectus et netus et malesuada fames ac turpis egestas*.

On the other hand, graphene-based antennas offer remarkable potential for advancements in wireless communication due to their unique properties, such as high conductivity, tunability, and flexibility. Future research should focus on characterizing the electromagnetic properties of graphene and other advanced materials, which could lead to improved antenna performance across various frequency bands. Significant opportunities lie in the development of terahertz antennas for high-speed short-range communications, as well as Quasi Yagi-Uda antennas for 6G applications. Additionally, further studies on graphene-based MIMO antennas for 5G could enhance efficiency and capacity, meeting the growing demand for high-speed connectivity. The use of graphene in affordable substrates like Kapton could also lead to cost-effective solutions for portable and wearable devices, expanding the market for next-generation electronics.

Moreover, exploring nano-antennas for IoT and remote sensing applications and optimizing high-frequency broadband antennas are crucial for effective connectivity in high-demand environments. The integration of wireless communication and power transfer using graphene-based nano-patch antennas presents another promising research direction.

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6. AUTHORS’ NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

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