Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1619839

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 8 - Issue 3: 824-830 / May 2025

# A COST-EFFECTIVE WIDE-BAND ANTENNA FOR 5G COMMUNICATION SYSTEMS

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**Abstract:** This study addresses the design of a wide-band microstrip patch antenna for 5G mobile communication systems. To respond to the increasing data rate and wide bandwidth needs in fifth-generation communication systems, it is very important to increase the performance of the antennas used. In this paper, a manufacturable and compact microstrip patch antenna design operating at 28 GHz wave frequency is realized and the simulation results are compared with the measured results. The proposed antenna is designed using a low-cost FR-4 substrate. The primary motivation behind calling the antenna "cost effective" in this study is the choice of the FR-4 substrate, which is significantly more affordable than other high-performance materials commonly used for 5G antennas, such as Rogers RT Duroid. Despite the limitations of FR4 substrate at high frequencies, this study demonstrates that a functional and efficient wide-band antenna can still be achieved through careful design and optimization. The performance of the antenna is evaluated with parameters such as input reflection coefficient ($S_{11}$), bandwidth, gain, and radiation efficiency of the antenna. The simulations of the proposed antenna are performed using CST and CEMS programs and the obtained results show that the antenna has a wide bandwidth of 1950 MHz between 26.85 GHz and 28.8 GHz. A parametric study of the antenna is performed to show the effect of substrate thickness and patch size on antenna performance. Numerical and measured results show that the proposed microstrip patch antenna has good performance for 5G communication systems, including wide bandwidth, high gain and low reflection coefficient. The antenna fabricated on the low-cost FR4 substrate can be useful for 5G communication systems with its cost-effectiveness and compact geometric configuration.

**Keywords:** 5G, Microstrip patch antenna, CST, CEMS, Low-cost antenna

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**Received:** January 14, 2025
**Accepted:** April 09, 2025
**Published:** May 15, 2025

**Cite as:** Kalınay G, Duru İ, Tabaru TE, Kaburcuk F. 2025. A cost-effective wide-band antenna for 5G communication systems. BSJ Eng Sci, 8(3): 824-830.

## 1. Introduction

The rapid development in communication industries has come with huge capacity and speed needs with the connection of devices to networks. Fourth generation (4G) communication technologies have been in use around the world since 2009 (Przesmycki et al., 2020). It is worth mentioning that the fifth generation (5G) is the updated version of 4G regarding speed, latency, capacity, and spectrum use, starting to take place in 2019 (Paul and Saha, 2021). Some unique features of 5G, which operate in several frequency ranges, can be listed as low cost, lower power consumption, vast area of coverage, strength of signal, and speed of data transfer (Darboe et al., 2019; Goyal and Shankar Modani, 2018a; Nahas, 2022). The main goal of 5G technology is faster and more reliable data transmission. The millimeter-wave band (mmWave) represents significant frequency ranges used in 5G networks. The mmWave frequency bands used for 5G connectivity are specified as 24.25-27.5, 27.5-29.5, 37-40, and 64-71 GHz (Lee et al., 2018). The 26 and 28 GHz frequency bands, determined by the Federal Communications Commission (FCC), are frequently encountered in the literature (Afif et al., 2020; Fonte et al., 2018; Lima De Paula et al., 2021). Additionally, some researchers have conducted studies to improve the radiation characteristics of microstrip antennas (Ezzulddin et al., 2022; Przesmycki et al., 2020). Due to their low profile, low cost, small size, and ease of production, microstrip patch antennas have become very effective in 5G wireless communication devices. Patch antennas stand out as planar antennas due to their low profiles and ease of integration into communication systems. Radiation characteristics, input reflection coefficients, gain values, and radiation patterns of patch antennas to be used in communication systems have been studied. To minimize the loss in the patch antenna, a low-loss dielectric material should be selected, the thickness of the substrate should be suitable for the designed antenna, the patch and ground plane materials should have good conductivity, proper grounding should be provided, and the feed line should be suitable for the impedance of the antenna. In patch antenna design, gain-size-application issues need to be optimized according to the desired specification. Patch antennas normally have gains between 2 dB and 12 dB (Kumar et al., 2023). Optimization of an antenna design is carried out to increase radiation efficiency and to decrease conductor losses by reducing surface roughness. Evaluated based on optimized values, performance of the antenna is assessed through parameters such as $S_{11}$, voltage standing wave ratio (VSWR), and radiation patterns. Another important parameter used in antenna evaluation is directivity, which ensures signals are transmitted more intensively and narrowly, thus preventing signal loss by sending high-powered signals. Increasing signal power improves transmission distance, which is crucial for wireless communication technologies. Increasing bandwidth and developing microstrip antennas with various methods are among the frequently discussed topics. To increase bandwidth, focus has been on slotting, using thicker substrates, selecting substrates with low permittivity, preferring structures with multiple resonances, and achieving impedance matching (Goyal and Shankar Modani, 2018b; Hakeem and Nahas, 2021; Jebabli et al., 2021). In antenna design for mobile communication systems, one of the challenges encountered is the lossy nature of the FR-4 substrate, a low-cost substrate, at high frequencies. Moreover, at high frequencies, the reduction in antenna size poses challenges such as soldering issues and precision limitations in manufacturing capabilities. There are various works available in the literature which present antennas operating in 5G frequencies featuring a beneficial bandwidth and geometry with an interesting gain. However, most of these were designed and manufactured on substrates of high cost and were not experimentally verified. However, in this study, a microstrip patch antenna designed and fabricated on a low-cost and lossy FR-4 substrate is proposed. Thus, the proposed antenna with lossy substrate provides suitable bandwidth, gain and input reflection coefficient values which make it a potential candidate for 5G systems, unlike antennas designed on high cost substrates as reported in the literature (Awan et al., 2019.; Fante et al., 2021; Przesmycki et al., 2020; Rahim et al., 2017; Yadav et al., 2021).

## 2. Materials and Methods

### 2.1. Antenna Geometry

The proposed antenna is designed and simulated to operate at 28 GHz on an FR-4 substrate. The geometry of the proposed microstrip antenna is shown in Figure 1 and its size parameters are tabulated in Table 1. The overall size of the antenna is 30 mm x 30 mm x 1.6 mm. The front surface of the substrate features a single radiating patch, while the back surface has a full ground plane. The design and analysis of the proposed antenna is carried out using the CST Student Version Software and a computational electromagnetic simulator (CEMS) software based on the finite-difference time-domain (FDTD) method. Thus, the consistency of the simulations is verified and tested for reliability before fabrication of the antenna. The proposed antenna is designed and simulated to operate at 28 GHz on an FR-4 substrate with a dielectric permittivity of 4.3, a thickness of 1.6 mm, and a loss tangent of 0.025. Numerical analysis of the antenna was conducted by a CEMS software based on the FDTD method (A. Z. Elsherbeni et al., 2016; V.Demir et al., 2021) as well as the CST Student Version software.

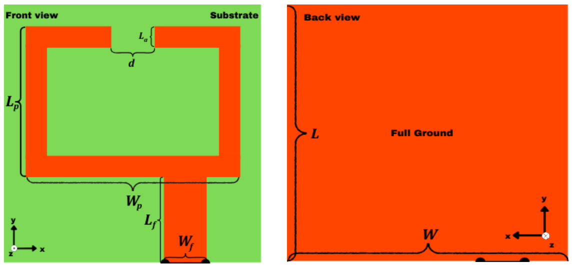


**Figure 1.** Front and back geometry of the proposed antenna.

When designing the antenna, it is essential to follow specific steps, namely the radiator patch design, feed line design, and matching element design. The most crucial parameters to consider during antenna design include the dielectric constant ($\varepsilon_r$) of the substrate, resonance frequency ($f_r$), and height of the substrate ($h$) (Balanis 2016; Goyal and Modani 2018).

The radiation efficiency is a crucial parameter for the antenna performance. For achieving good radiation efficiency, a practical width ($W$) is given as equality (equation 1) with the speed of light in free space $v_0$.

$$W = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

The effective dielectric constant of a ($\varepsilon_{reff}$) microstrip antenna is calculated using $\varepsilon_r$, $h$, and $W$ in equation 2.

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} + \frac{1}{\sqrt{1 + 12\frac{h}{W}}} \tag{2}$$

The extension length ($\Delta L$) are calculated using effective dielectric constant $(\varepsilon_{reff})$, $h$, and $W$ in equation 3.

$$\Delta L = 0.412h\frac{(\varepsilon_{reff} + 0.3)(\frac{W}{h} + 0.264)}{(\varepsilon_{reff} - 0.258)(\frac{W}{h} + 0.8)} \tag{3}$$

For the patch antenna, the main length ($L$) is formulated using equation 4, which involves the speed of light in free space $v_0$, effective dielectric constant $(\varepsilon_{reff})$, and extension length ($\Delta L$).

$$L = \frac{v_0}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{4}$$

For a given characteristic impedance $Z_0$ and dielectric constant ($\varepsilon_r$), it is expressed with the following equations 5 and 6 under the condition $\frac{W}{h} > 2$.

$$\frac{W}{h} = \frac{8e^{A}}{e^{2A} - 2} \qquad (5)$$

$$A = \frac{z_o}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}(0.23 + \frac{0.11}{\varepsilon_r}) \qquad (6)$$

A quarter-wave transformer is a microstrip line used to match impedance mismatches. It aligns the impedance between the microstrip line and the width of the rectangular patch antenna along its center point. The equation for the quarter-wave transformer is given by the following equality (equation 7).

$$L_t = \frac{\lambda_g}{4} \qquad (7)$$

The guided wavelength $\lambda_g$ is given by the following equation 8.

$$\lambda_g = \frac{\lambda_o}{\sqrt{\varepsilon_r}} \qquad (8)$$

The impedance equation for a quarter-wave transformer is given by the following equation 9.

$$Z_t = \sqrt{Z_o Z_p} \qquad (9)$$

Assuming the feed line impedance $Z_o$ is 50 Ω, $Z_p$ denotes the impedance obtained across the width of the patch element. When resonance occurs, the input impedance at the center point is given by the following equations 10 and 11:

$$Z_p = \frac{1}{2G_1} \qquad (10)$$

where;

$$G_1 \begin{cases} \frac{1}{90}(\frac{W}{\lambda_o})^2 & W \leq \lambda_o \\ \frac{1}{120}(\frac{W}{\lambda_o}) & W \geq \lambda_o \end{cases} \qquad (11)$$

**2.2. CEMS Simulation Parameters**

When using the CEMS simulation, the problem domain is divided into cubic cells. The accuracy of the solution directly depends on the selection of cell sizes (Kaburcuk et al., 2021). To ensure numerical stability of the antenna, the cell size must be smaller than 1/20th of the shortest wavelength ($\lambda_{min}$) in the problem domain. For the numerical stability in the antenna simulation, a cell size is set uniformly to 0.1 mm in all directions. The CST Student Version Software is utilized to validate the accuracy of the FDTD-based CEMS simulation.

**2.3. Parametric Study of the Proposed Antenna**

**2.3.1. Substrate thickness effects**

In this study, the parametric study has focused on the effects of the substrate thickness ($h$) has upon the performance of the antenna, which was evaluated by means of the $S_{11}$ (dB) in Figure 2. Three values of substrate thicknesses were investigated: 1 mm, 1.6 mm, and 2 mm. The following analysis is based on $S_{11}$ parameters for each of those thickness values. Also these parametric studies were obtained using the CEMS. This parametric study presents that the antenna with a substrate thickness of 1.6 mm provides better performance for $S_{11}$ values at the frequency of 28 GHz.

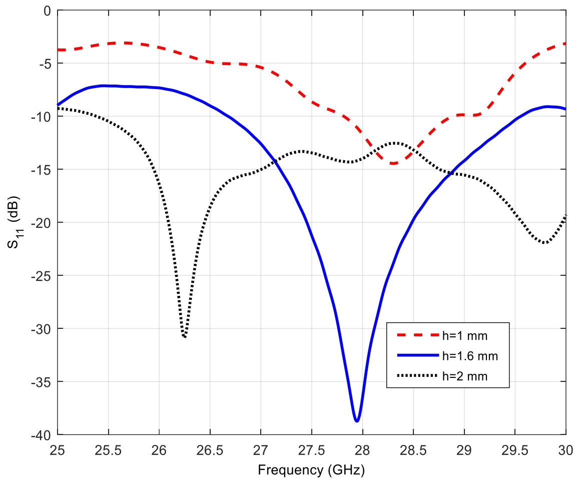


**Figure 2.** $S_{11}$ obtained using CEMS for different thicknesses of FR-4 substrate (1, 1.6, and 2 mm)

**2.3.2. Effect of distance between two radiation arms of antenna on S11 performance**

This section presents a parametric study to show the effect of a slot distance between two radiation arms in the proposed antenna on $S_{11}$ performance of the antenna at around 28 GHz. The simulations of the antenna have been performed when the slot distance between two radiation arms is 3, 5, and 7 mm. Figure 3 shows the $S_{11}$ of the antenna for the slot distance of 3, 5, and 7 mm. The best performance for $S_{11}$ values at aroud 28 GHz has been achieved when the slot distance is 5 mm. The minimum value of $S_{11}$ is approximately -38 dB, indicating very good resonance and energy transmission efficiency at 28 GHz.

Based on these two parameteric studies, the configuration of the proposed antenna has been determined to obtain a comparatively better performance for the antenna at 28 GHz. The dimensions of the proposed antenna are provided in Table 1.

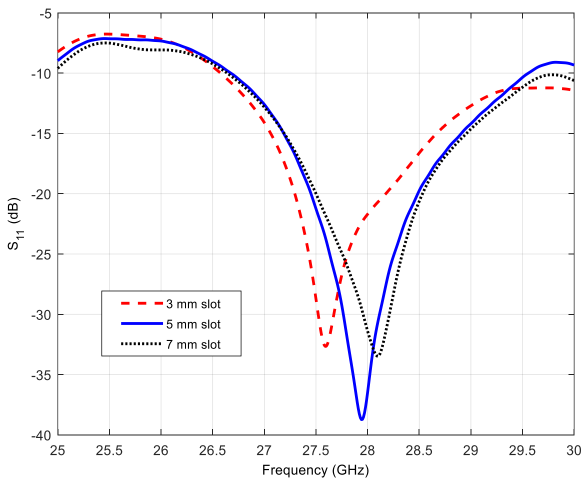


**Figure 3.** Simulated $S_{11}$ for the slot distances of 3, 5, and 7 mm.

**Table 1.** Dimensions of the Proposed Antenna

| Parameter | L | W | $L_p$ | $W_p$ | $W_f$ | $L_f$ | $L_a$ | h | d |
|---|---|---|---|---|---|---|---|---|---|
| Dimension (mm) | 30 | 30 | 17.5 | 25 | 5 | 10 | 5 | 1.6 | 5 |

## 4. Results and Discussion

### 4.1. Comparison of Simulated and Measured Results

The simulated and measured $S_{11}$ of the proposed antenna obtained using both CEMS and CST simulators are shown in Figure 4 with good consistency between them. The $S_{11}$ value at 28 GHz is around-19.5 dB obtained using CST, whereas it is around -35 dB obtained using CEMS at 28 GHz. The measured $S_{11}$ value of the fabricated antenna at 28 GHz is about -25 dB. The $S_{11}$ measurement over the frequency range has been performed using the Anritsu brand network analyzer. The difference between simulation and measured results can be caused by: SMA connector losses, soldering mistakes, imperfections during manufacturing, and even coaxial cable losses.

The gain performance of the antenna was analyzed across three different planes and shown in Figure 5 obtained by CEMS. The maximum values of the gain in the x-y, x-z, and y-z planes are 2.54, 8.29, 8.04 dBi at 28 GHz. All results obtained by CEMS and CST highlight that the antenna provides very strong radiation performance with high gain, wide bandwidth, and proper efficiency at 28 GHz, making it suitable for 5G communication applications.

**Table 2.** Simulation and measurement performances of the proposed antenna

| | Resonance Freq. (GHz) | $S_{11}$ (dB) | Freq. Range (GHz) | Gain (dBi) | Bandwidth (MHz) |
|---|---|---|---|---|---|
| Simulation (CST) | 28.04 | -19.5 | 23-31.2 | 6.52 | 8200 |
| Simulation (CEMS) | 27.85 | -38 | 26.7-29.6 | 8.29 | 2900 |
| Measurement | 27.8 | -25 | 26.85-28.8 | - | 1950 |

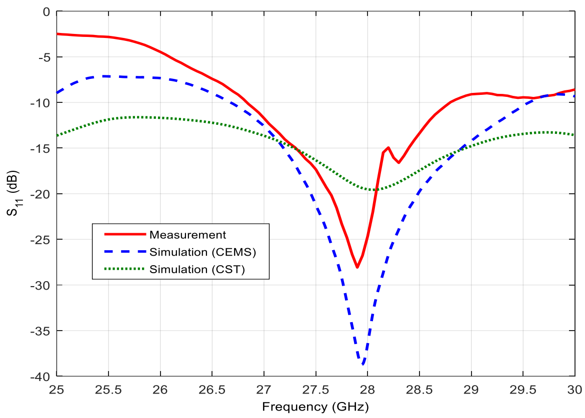


**Figure 4.** Comparison of measured and simulated $S_{11}$ obtained using CEMS and CST.

The front and back views of the fabricated antenna are shown in Figure 6. For comparison purposes, the simulated and measured results of the proposed antenna are given in Table 3. Table 3 shows the trade-off between cost, bandwidth, and performance. While some studies have achieved a wider bandwidth with FR-4, it is known that bandwidth is not the sole criterion for antenna performance. Other factors such as gain, input reflection coefficient ($S_{11}$), and fabrication feasibility also play a significant role in determining the overall efficiency of an antenna. Our study establishes a balance between these parameters while ensuring manufacturability. This study for the 5G antennas aims to improve performance using cost-effective substrate and serving as an alternative to antennas on more expensive substrates.

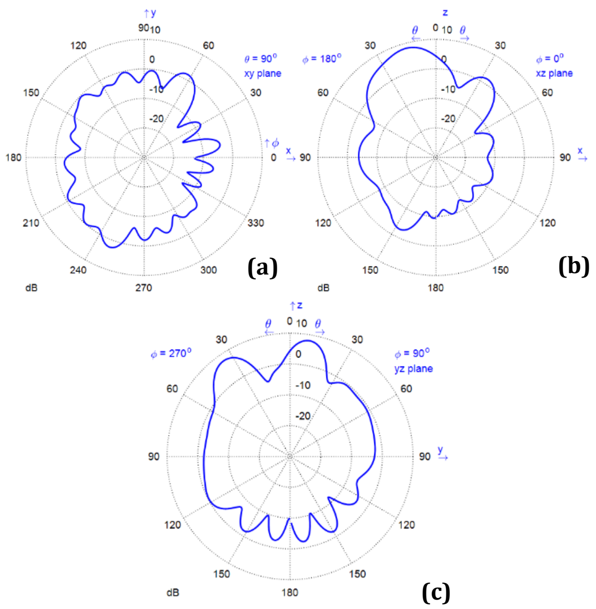


**Figure 5.** Gain patterns of the antenna on x-y (a), x-z (b) and y-z (c) planes at 28 GHz obtained using CEMS.

This study successfully demonstrates the design and fabrication of a wideband microstrip patch antenna operating at 28 GHz for 5G mobile communication systems. A low-cost FR-4 substrate, which is very well known to have limitations at high-frequency applications, is used in the antenna design. The proposed antenna design has been optimized to strike a balance between performance and cost-effectiveness. A parametric study was conducted on substrate thickness and slot size for optimum performance at target frequencies. The antenna was analyzed very rigorously using CST and CEMS



(c)

simulation tools for key performance measurements: input reflection coefficient, bandwidth and gain. A very good agreement was obtained between the simulated and measured results.

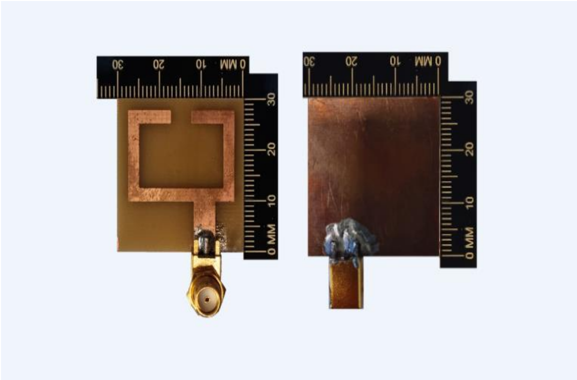

**Figure 6.** Front and back views of the fabricated antenna.

The measurement results show that the proposed antenna has a bandwidth of 1950 MHz and operates in the frequency range of 26.85 to 28.8 GHz. The measured input reflection coefficient of the antenna is around -25 dB at 28 GHz.

It also validates the antenna performance comparison with similar antennas in the literature, highlighting the competitive advantage in cost-sensitive applications where the use of high-performance antennas may not be suitable, especially on expensive substrates. Therefore, the proposed design offers a promising solution for 5G wireless communications where compactness, high gain, and wide bandwidth are critical. Overall, this design represents an effective and feasible alternative that can be successfully used in small-sized 5G devices with very good performance when considering the cost, and therefore would be a good candidate to be integrated into a future 5G communication system.

**Table 3.** A comparison of patch antenna at 28 GHz and previous works

| Ref. No | Substrate | Frequency Range (GHz) | Resonance Frequency (GHz) | Reflection Coeff. (dB) | Gain (dBi) | BW (GHz) |
|---|---|---|---|---|---|---|
| (Darboe et al., 2019) * | RT Duroid 5880 | 27.95-28.38 | 27.95 | -13.48 | 6.63 | 0.847 |
| (Goyal and Shankar Modani, 2018b) * | Roger RT 5880 | 27.53-28.60 | 28.06 | -17.4 | 6.72 | 1.1 |
| (Mashade and Hegazy, 2018) * | FR-4 | 28 | 27.90 | -15.35 | 6.92 | - |
| (Hussain et al., 2021) ** | ROGERS 4003 | 26.5 – 32.9 | - | 35.8 | 5.42 | 6.4 |
| (Sellak et al., 2020) * | Taconic TLY-5 type | 27.98-28.21 | 27.98 | -36.17 | 6.71 | 0.23 |
| (Mohammed et al., 2021) * | Air substrate | - | 28 | -39.49 | 9.55 | 1.72 |
| (Merlin Teresa and Umamaheswari, 2022) * | FR-4 | 26.84-28 | 27.99 | -27.79 | 6.37 | 2.62 |
| (Hasan et al., 2022) * | Different materials (Rogers, Taconic, FR-4, Foam, RT Duroid) | - | 28 | (-26.24, -14.60) CST and HFSS | (5.39, 5.94) CST and HFSS | (0.708, 0.503 ) CST and HFSS |
| (Yadav et al., 2021) * | Rogers RT /duroid 5880 | 27.08-28.85 | 28 | -33.50 | 9.04 | 1.767 |
| (Mistri et al.,2023)** | Rogers RO4003 | 23.56-28.25 | 27.04-27.98 | -21 | 6.65 | 4.69 |
| (Munusami and Venkatesan, 2024)** | FR-4 | 26.04-28.44 | 27 | -49.4 | 6.27 | 2.4 |
| (Chowdhury et al.,2024)** | FR-4 | 26-29.4 | 28 | -58.14 | 6.02 | 3.4 |
| (Prop.) ** | FR-4 | 26.85-28.8 | 28 | -27 | - | 1950 |
| (Kaburcuk et al., 2021) ** | FR-4 | 24-28 | 28.2 | -32.72 | 3.20<br>3.99 | 24 GHz<br>28 GHz |

*Simulation Study

**Simulation and Fabrication Study

**Author Contributions**

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

| | G.K. | İ.D. | T.E.T. | F.K. |
|---|---|---|---|---|
| C | 25 | 25 | 25 | 25 |
| D | 30 | 30 | 20 | 20 |
| S | - | - | 40 | 60 |
| DCP | 30 | 20 | 25 | 25 |
| DAI | 30 | 20 | 25 | 25 |
| L | 30 | 30 | 20 | 20 |
| W | 35 | 35 | 10 | 20 |
| CR | 30 | 30 | 20 | 20 |
| SR | 30 | 30 | 20 | 20 |
| PM | 20 | 20 | 30 | 30 |
| FA | 25 | 25 | 25 | 25 |

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

**Conflict of Interest**

The authors declared that there is no conflict of interest.

**Ethical Consideration**

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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