Indian Journal of History of Science (2026) 61:1–8
https://doi.org/10.1007/s43539-026-00211-9

ARTICLE

A simple 4-step method for constructing 4 × 4 pandiagonal magic squares

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Received: 8 January 2026 / Accepted: 24 March 2026 / Published online: 25 April 2026

Abstract
Magic squares, particularly the 4 × 4 pandiagonal (PD) ones, offer a distinct allure because of the property that rows, columns, principal diagonals, as well as all the broken diagonals, give the magic sum. Building on our earlier exploration of Nārāyaṇa Paṇḍita's horse-move (*turagagati*) method, and drawing in particular on additional properties identified in a recent study, this paper presents a simple four-step procedure for constructing PD magic squares within a novel quadrilayered framework. In this method, we begin with four arbitrary numbers {a,b,c,d}, and from them generate the entire PD magic square in just four steps. Additionally, we also find that the characteristic polynomial satisfied by such a square (considering it as a matrix) takes a much simpler and elegant form than the one that is available in the literature.

Keywords Magic squares · Pandiagonal · *Bhadragaṇita* · Quadrilayered framework · Characteristic polynomial

1 Introduction

Magic squares have long fascinated both scholars and the common man, captivating them in different ways through their blend of fun with arithmetic, and combinatorial ingenuity. Contemporary research has extended this fascination by uncovering deeper structural complexities and by developing algebraic and visual tools for their systematic analysis (Al-Ashhab & Al-Qdah, 2022; Mandadi et al., 2024; Mattingly, 2000). In the Indian mathematical tradition, the study of magic squares, referred to as *Bhadragaṇita*, was extensively carried out by the 14th-century scholar Nārāyaṇa Paṇḍita in his monumental treatise *Gaṇitakaumudī* (Dvivedi, 1942; Kusuba, 1993; Singh, 2002). Nārāyaṇa's treatment of the pandiagonal (PD) magic squares is especially noteworthy, exhibiting distinctive structural features that make it a natural testbed for deeper analysis.

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This paper introduces a novel 4-step method for the construction and analysis of 4×4 PD magic squares. Here, starting from a chosen reference cell, we first determine the four horse-move (HM) cells relative to it and then proceed outward to adjacent and boundary cells. The present study builds upon our earlier study of Nārāyaṇa Paṇḍita's *Turagagati* method for 4×4 PD magic squares (Mandadi et al., 2024), which employs arithmetic sequences and HMs to realise PD structures.

The paper is structured as follows: Section 2 provides background and a brief literature review situating the present work alongside prior studies, including our group's earlier work on the *Turagagati* method. Section 3 lists a few core properties satisfied by 4×4 PD squares that form the bedrock for our discussion in the following section. Section 4 systematically describes the 4-steps involved in detail—including the decomposition $M = M_0 + kJ_4$ and the role of HM cells. Section 5 discusses the *characteristic polynomial* for a 4×4 pandiagonal (PD) magic square that is obtained by using the quadrilayered construction proposed by us. Section 6 offers concluding remarks and outlines directions for further study.

2 Background and related work

As indicated earlier, the present study builds upon the previous research by our group (Mandadi et al., 2024), which focused on identifying the foundational properties of 4×4 pandiagonal (PD) magic squares. In that work, by

m_{11}	m_{12}	m_{13}	m_{14}
m_{21}	m_{22}	m_{23}	m_{24}
m_{31}	m_{32}	m_{33}	m_{34}
m_{41}	m_{42}	m_{43}	m_{44}

Fig. 1 A typical PD magic square *M* with generic elements

considering a general 4×4 PD magic square $M = [m_{ij}]_{4\times4}$ (see Fig. 1), we investigated various properties that such squares must satisfy. We not only verified some of the results documented by earlier scholars (Rosser & Walker, 1938; Sridharan & Srinivas 2011; Vijayaraghavan, 1941) but also identified and proved additional properties intrinsic to the pandiagonal structure.

Whereas the earlier work was primarily intended to elucidate the *Turagagati* method for constructing the PD magic square as described by Nārāyaṇa, the present study shows that a careful examination of the properties of PD squares makes it possible to propose other, equally elegant methods of construction. The present paper is essentially an outcome of these investigations and introduces a novel 4-step method. Here we conceptualise the 4×4 PD magic square as a series of interdependent layers, each contributing to the overall pandiagonal property. It so happens that this novel approach naturally leads to discovering other interesting features.

In this approach, the construction of a PD square basically commences with a set of four numbers, say $\{a, b, c, d\}$ of our choice, and placing them in the four HM positions as shown in Fig. 2. This initial choice uniquely determines all the remaining entries of the magic square. In other words, the sixteen elements of the PD magic square correspond to the elements of the powerset $\mathcal{P}(\{a, b, c, d\})$.

Alongside our contributions, a rich body of work has examined magic squares through algebraic, combinatorial lenses. Researchers have increasingly applied linear algebraic techniques to analyse their properties. Stephens (1993) explored magic squares of orders four and five through their eigenvalues and characteristic polynomials. Moler (1993), using MATLAB, observed that magic squares of odd order yield nonsingular matrices, whereas even-order magic squares are singular. Mattingly (2000) sharpened this result by showing that even-order 'regular' magic squares necessarily admit one zero eigenvalue.

Extending further into applications, Al-Ashhab & Al-Qdah (2022) studied even-ordered magic squares (orders 4, 6, and 8) with an emphasis on characteristic polynomials and eigenvalues, drawing connections to cryptography and secure communication.

This spectrum of research underscores both the theoretical and applied significance of magic squares. Historically valued as *Bhadragaṇita*, they remain objects of cultural importance and mathematical curiosity. Theoretically, they serve as fertile ground for combinatorial and algebraic exploration; practically, they connect with domains such as encryption and data security. More importantly, the process of generating magic squares is inherently enjoyable, and when introduced at an early stage, it can significantly enhance a child's arithmetic skills, besides being an activity that would generate a lot of fun.

Against this backdrop, the simple 4-step method we propose offers a complementary perspective: it highlights the hierarchical organisation of 4×4 PD magic squares, recasts known algebraic conditions in a layered form, and reveals new structural properties that emerge from this representation, which is also revealed through the characteristic polynomial. Before presenting this novel method, we first summarise in Sect. 3 the key properties of 4×4 PD magic squares that serve as prerequisites for our analysis.

3 Properties satisfied by 4×4 pandiagonal magic squares

Here we merely present the principal properties satisfied by 4×4 PD magic squares that form the basis for the four-step method described in Sect. 4. A detailed discussion and proofs of the properties are available in our earlier work (Mandadi et al., 2024). The four properties that are relevant for our discussion are:

Property 1: The sum of the entries of any 2×2 subsquare of any 4×4 pandiagonal magic square, including those that wrap toroidally around the edges, equals its magic sum.

If $M = [m_{ij}]_{4\times4}$ denotes a 4×4 PD magic square with magic sum *S*, then this property may be expressed as:

$$m_{ij} + m_{(i+1)j} + m_{i(j+1)} + m_{(i+1)(j+1)} = S. \tag{1}$$

Note: In the above equation, as well as in all our discussions henceforth, indices are interpreted modulo 4 (viz., $m_{(i+4)j} = m_{ij}$ and $m_{i(j+4)} = m_{ij}$). It may also be mentioned here that this property appears as early as the 10^{th} century in Bhaṭṭotpala's (c. 950) commentary on the *Gandhayukti* section of Varāhamihira's *Bṛhatsaṃhitā* (Jha, 2014).

Property 2: The sum of two cells separated by one intervening cell, along a diagonal, equals half the magic sum.

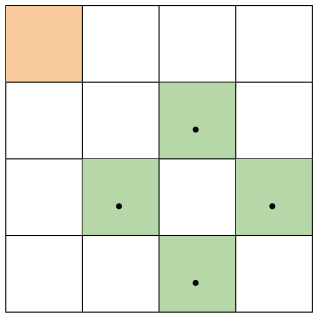

Fig. 2 The only four possible HM cells for m_{11}

For convenience in our discussion, such cells along the diagonal with one intervening cell between them are referred to as antipodal cells. For example, m_{11} is antipodal to m_{33}; m_{21} is antipodal to m_{43} and so on. The sum of elements in any two antipodal cells is equal to $\frac{S}{2}$. In general,

$$m_{ij} + m_{(i+2)(j+2)} = \frac{S}{2}. \tag{2}$$

It is worth noting that this property was identified and has been noted explicitly in the 16th century text *Smṛtitattva* by Raghunandana Bhaṭṭācārya (Vidyasagara, 1895). In his text, Raghunandana outlines the procedure to fill eight cells with numbers $1, 2, \ldots, 8$, and then instructs the reader to fill the remaining eight cells based on the above property to produce 4×4 PD magic squares with the desired magic sum.

Property 3: The sum of elements in any two cells that are diagonally adjacent, or separated by one cell along a row or column, equals the sum of the elements in the only two cells that are simultaneously in horse-move positions relative to those two (chosen) cells.

In a 4×4 PD magic square, for any given cell, there are only four cells that are in HM relationship with it. We refer to them as HM cells. For instance, the only four cells that are in HM with m_{11} are $(m_{23}, m_{32}, m_{34}, m_{43})$, which is illustrated in Fig. 2. In general, for a given cell m_{ij}, these four HM cells are:

$$\{\, m_{(i+1)(j+2)},\ m_{(i+2)(j+1)},\ m_{(i+2)(j+3)},\ m_{(i+3)(j+2)} \,\}.$$

It is also noteworthy that these are always diagonally connected to each other.

Choosing any pair among these four HM cells, say (m_{23}, m_{32}), we find that the sum of elements in them is always equal to the sum of the elements in the other two cells (m_{11}, m_{44}) that are simultaneously in HM with these cells. That is,

$$(m_{23} + m_{32}) = (m_{11} + m_{44}). \tag{3}$$

If we were to choose (m_{23}, m_{43}), then the relationship that would be satisfied is:

$$(m_{23} + m_{43}) = (m_{11} + m_{31}). \tag{4}$$

Similarly, if we were to choose (m_{23}, m_{34}), then the relationship would be:

$$(m_{23} + m_{34}) = (m_{11} + m_{42}). \tag{5}$$

Property 4: For any given cell, the difference between the sum of the elements in its four horse-move cells and twice the element in the cell itself yields half the magic sum.

For instance, if we choose m_{11}, then this relationship may be expressed as:

$$(m_{23} + m_{32} + m_{34} + m_{43}) - 2m_{11} = \frac{S}{2}. \tag{6}$$

In general, for any cell m_{ij}, the relation that will be satisfied is:

$$(m_{(i+1)(j+2)} + m_{(i+2)(j+1)} + m_{(i+2)(j+3)} + m_{(i+3)(j+2)}) - 2m_{ij} = \frac{S}{2}. \tag{7}$$

From a historical perspective, we would like to add that Rosser and Walker, in their 1938 paper, had proved the first two properties. As regards Property 4, it was first indicated by Vijayaraghavan (1941). In our previous work (Mandadi et al., 2024), we have provided a proof of it.

4 The 4-step method

In this section, we describe the 4-steps involved in generating 4×4 PD magic squares by filling their cells in 4 layers in a sequential manner. Here, we start with the construction of a *zero-element* PD magic square (denoted by M_0 hereafter). By this, we mean a PD magic square M_0 whose (1,1) element is zero (i.e., $m'_{11} = 0$). As we shall see later, this choice is just for the sake of elegance and convenience without loss of generality. Now we proceed with the description of how the four-layered construction is done.

4.1 Construction of layer 1

Here we just fill two cells (m'_{11} and m'_{33}). Since M_0 is a zero-element PD square, we begin by placing zero in the cell m'_{11}. By property 2, the sum of antipodal cells is equal to $\frac{S_0}{2}$. Thus,

$$m'_{11} + m'_{33} = \frac{S_0}{2}. \tag{8}$$

Hence,

$$m'_{33} = \frac{S_0}{2} - m'_{11} = \frac{S_0}{2}. \tag{9}$$

The configuration of the magic square at this stage is depicted in Fig. 3.

4.2 Construction of layer 2

Here we will be filling four cells with m'_{33} as the epicentre. In fact, m'_{33} could be conceived as the nodal cell around which other layers also emerge. The four cells that get filled at this stage are all in HM positions with respect to m'_{11}, viz. m'_{23}, m'_{34}, m'_{43}, and m'_{32}. We fill them with the four numbers a, b, c, and d respectively.

From (6), since $m'_{11} = 0$, we have,

$$S_0 = 2(a + b + c + d). \tag{10}$$

Also from (9),

$$m'_{33} = a + b + c + d. \tag{11}$$

The configuration of the magic square at this stage is depicted in Fig. 4.

4.3 Construction of layer 3

At this stage, we will be filling the cells adjacent to the four cells filled in Layer 2. Since these adjacent cells overlap, there are effectively 6 cells (viz. $m'_{13}, m'_{22}, m'_{24}, m'_{31}, m'_{42}, m'_{44}$) that are to be filled. We observe that for every cell given in this layer, there are only two cells in Layer 2 that are simultaneously in HM with the chosen cell. For instance, m'_{13} is simultaneously in HM with m'_{34} and m'_{32}. By Property 3, we have,

$$\begin{aligned} m'_{13} + m'_{11} &= m'_{34} + m'_{32} \\ &= b + d \end{aligned} \tag{12}$$

Since $m'_{11} = 0$, we get,

$$m'_{13} = b + d \tag{13}$$

0			
		$\frac{S_0}{2}$	

Fig. 3 Magic square M_0 with the first layer filled

0			
		a	
	d	$a+b$ $+c+d$	b
		c	

Fig. 4 Magic square M_0 with the first two layers filled

Similarly, we get the values of the other elements in this layer as follows:

$$\begin{aligned} m'_{22} &= b + c \\ m'_{24} &= c + d \\ m'_{31} &= a + c \\ m'_{42} &= a + b \\ m'_{44} &= a + d. \end{aligned} \tag{14}$$

The configuration of the magic square at this stage is depicted in Fig. 5.

4.4 Construction of layer 4

After the formation of three layers, we are left with only four empty cells to be filled. It must be noted that these cells are antipodal cells to the four cells filled in Layer 2. By Property 2, the sum of elements in a cell and its antipodal cell is $\frac{S_0}{2}$. Hence, we have,

$$m'_{21} + m'_{43} = \frac{S_0}{2} = a + b + c + d. \tag{15}$$

0		$b+d$	
	$b+c$	a	$c+d$
$a+c$	d	$a+b$ $+c+d$	b
	$a+b$	c	$a+d$

Fig. 5 Magic square M_0 with the first three layers filled

Since $m'_{43} = c$, we get,

$$m'_{21} = a + b + d. \tag{16}$$

Similarly, one can show that:

$$\begin{aligned} m'_{12} &= a + c + d, \\ m'_{14} &= a + b + c, \\ m'_{41} &= b + c + d. \end{aligned} \tag{17}$$

Filling in these values, the magic square M_0 becomes complete (see Fig. 6). It is noteworthy that the 16 elements of this PD magic square can be visualised as the constituents of the powerset of $\{a, b, c, d\}$ as shown in Table 1, with the connotation that the subset $\{a, b\}$ corresponds to the cell containing the value $a + b$, and $\{a, b, c\}$ corresponds to the cell containing the value $a + b + c$ and so on.

It may be reiterated that the configuration of the magic square depicted in Fig. 6 has been obtained purely based on the properties displayed by the PD squares that were listed in Sect. 3 earlier. Naturally, the resulting square is PD.

4.5 Decomposing any 4×4 PD magic square

Thus far, we have demonstrated the construction of a 4×4 magic square using a simple 4-step quadrilayered approach. The only constraint imposed was that one of the elements be zero—a deliberate choice made for structural elegance and simplicity. In general, any 4×4 PD magic square M can be decomposed into two parts: a zero-element PD magic square M_0 and a scalar k times *all-ones matrix*, denoted by J_4,

$$M \; = \; M_0 \; + \; kJ_4. \tag{18}$$

If S denotes the magic sum of M, then

$$S \; = \; S_0 \; + \; 4k. \tag{19}$$

This decomposition shows that, given any PD magic square, there exists an essential quadrilayered structure similar to the zero-element PD magic square. This can be seen in Fig. 7.

The first such parameterisation was indicated by Vijayaraghavan (1941). He primarily utilises the following two properties to arrive at his general form:

> The arrangement is effected in conformity with the results that (1) the sum of any two adjacent numbers in any row (column) is equal to the sum of the corresponding numbers in the alternate row (column), and, (2) the sum of any two alternate numbers in any diagonal line is S.

The general form given by him, using 4 parameters a, b, P, R and magic sum $2S$, is shown in Fig. 8. While his method of construction is based solely on these properties, our approach differs significantly in its underlying concept. Instead of relying on a fixed set of rules for every cell, our 4-step method employs a layered construction. This provides greater structural transparency, making it visually and logically more intuitive.

Table 1 Mapping the elements of powerset $\mathcal{P}(\{a, b, c, d\})$ to their respective layers.

Superset	Subset	Layer
$\mathcal{P}(\{a, b, c, d\})$	$\varnothing, \{a, b, c, d\}$	1
	$\{a\}, \{b\}, \{c\}, \{d\}$	2
	$\{a, b\}, \{a, c\}, \{a, d\}, \{b, c\}, \{b, d\}, \{c, d\}$	3
	$\{a, b, c\}, \{a, b, d\}, \{a, c, d\}, \{b, c, d\}$	4

0	$a+c+d$	$b+d$	$a+b+c$
$a+b+d$	$b+c$	a	$c+d$
$a+c$	d	$a+b+c+d$	b
$b+c+d$	$a+b$	c	$a+d$

Fig. 6 The general structure of a zero-element PD magic square M_0.

4.6 Illustrative examples

Let us consider the following examples to understand how the quadrilayered concept can be applied for the

k	$k+a+c+d$	$k+b+d$	$k+a+b+c$
$k+a+b+d$	$k+b+c$	$k+a$	$k+c+d$
$k+a+c$	$k+d$	$k+a+b+c+d$	$k+b$
$k+b+c+d$	$k+a+b$	$k+c$	$k+a+d$

Fig. 7 General quadrilayered form of a 4×4 PD magic square M

a	$R - a$	$S - (P - a)$	$S - \{R - (P - a)\}$
$S - (P - b)$	$S - \{R - (P - b)\}$	b	$R - b$
$P - a$	$R - (P - a)$	$S - a$	$S - (R - a)$
$S - b$	$S - (R - b)$	$P - b$	$R - (P - b)$

Fig. 8 General form of a 4×4 PD magic square given by Vijayaraghavan

0			
		27	

(a) Layer 1

		2	
0			
		4	
	8	27	13

(b) Layers 1 and 2

	17	2	12
0		21	
	15	4	10
6	8	27	13

(c) Layers 1, 2 and 3

23	17	2	12
0	14	21	19
25	15	4	10
6	8	27	13

(d) Layers 1,2,3 and 4

Fig. 9 Example 1: layer-wise construction of PD magic square

construction of a magic square of a given magic sum. These examples fall into two categories:

- PD magic square with all positive elements except one element being zero.
- PD magic square with all positive elements.

4.6.1 Example 1: PD magic square with one zero element

We want to construct a PD magic square whose magic sum is 54. Assume that one element, say m'_{21}, is zero. The element m'_{43}, which is antipodal, is $S_0/2$ (= 27). These two numbers form Layer 1. Now we need to choose four numbers $\{a, b, c, d\}$ such that their sum is $S_0/2$. One such choice is $\{2, 4, 8, 13\}$. By filling the square with these numbers, we complete Layer 2. The numbers that constitute the other two layers are given below (see Fig. 9c and d).

We get the four layers as follows:

Layer 1 $= 0, 27.$
Layer 2 $= 2, 4, 8, 13.$
Layer 3 $= 6, 10, 12, 15, 17, 21.$
Layer 4 $= 14, 19, 23, 25.$

The four-layered construction of this PD magic square is illustrated in Fig. 9.

4.6.2 Example 2: PD magic square with non-zero elements

Here, we would like to illustrate the construction of a PD magic square with a magic sum of 72 using the quadrilayered approach. Instead of choosing the smallest element, say m_{11}, as 0, we choose 2. For ease and simplicity, first we construct an intermediate zero-element PD magic square M_0 which has the magic sum $(S_0) = 72 - 4m_{11} = 64$ and $m'_{11} = 0$. The element m'_{33}, which is antipodal, is $S_0/2$ (= 32). In this example, we choose $\{4, 7, 8, 13\}$ as $\{a, b, c, d\}$ such that their sum is 32. The obtained intermediate zero-element PD magic square M_0 and the desired M are shown in Fig. 10a and b, respectively.

5 Characteristic polynomial

In this section, we review the formulation of Al-Ashhab & Al-Qdah (2022) for 4×4 PD magic square and then study the characteristic polynomial that arises from the quadrilayered framework that we have discussed above.

5.1 Al-Ashhab and Al-Qdah formulation

In their recent publication, Al-Ashhab & Al-Qdah (2022) have considered a general symbolic representation of a 4×4 PD magic square. Their construction expresses the square in terms of five independent parameters A, B, C, E, and magic sum $2s$ (see Fig. 11).

For the magic square given in Fig. 11, they have also arrived at an expression for its characteristic polynomial, which is given by

$$f(\lambda) = \lambda(\lambda - 2s)(\lambda^2 + 4\Theta), \tag{20}$$

where Θ is,

$$\begin{aligned}\Theta = {} & C^2 - A^2 - (s)^2 - AE - 2BE - CE \\ & - AB + BC + s(2E + 2A + B - C).\end{aligned} \tag{21}$$

0	25	20	19
24	15	4	21
12	13	32	7
28	11	8	17

(a) Zero-element PD (magic sum 64)

2	27	22	21
26	17	6	23
14	15	34	9
30	13	10	19

(b) PD magic square (magic sum 72)

Fig. 10 Example 2: PD magic square along with the intermediate zero-element magic square

A	B	C	$2s - B - C - A$
E	$2s - B - A - E$	$A + E - C$	$B + C - E$
$s - C$	$A + B + C - s$	$s - A$	$s - B$
$C + s - A - E$	$s - C - B + E$	$s - E$	$A + B + E - s$

Fig. 11 Configuration of a general 4×4 PD magic square given by Al-Ashhab & Al-Qdah (2022)

It is straightaway seen from (20) that one of the eigenvalues is 0, and the other is the magic sum. The computation of the other two eigenvalues is a bit more involved since the expression for Θ is a bit lengthy and involved.

5.2 Characteristic polynomial for quadrilayered construction

In the quadrilayered framework, the configuration of a general 4×4 PD magic square (see Fig. 7) is expressed in terms of a, b, c, d and k. For this form, the characteristic polynomial is

$$f(\lambda) = \lambda(\lambda - S)(\lambda^2 - 4(ad + bc)). \tag{22}$$

The roots of the polynomial are

$$\lambda = 0, S, \pm 2\sqrt{ad + bc}.$$

Comparing the two characteristic polynomials given by (20) and (22), we notice that they are structurally identical with the only difference in Θ, which is given by

$$\Theta = ad + bc. \tag{23}$$

In the quadrilayered construction we have proposed, it is seen that the expression for Θ given by (23) is considerably simpler than the expression for Θ given by (21). It may also be noted that Θ involves only four parameters instead of five. Furthermore, since the expression is quite compact, it also enhances the computational ease.

6 Conclusion

This study introduced a novel quadrilayered framework for conceptualising and constructing 4×4 PD magic squares. By dissecting these intricate mathematical constructs in the form of PD squares, whose elements display some wonderful mathematical properties, we have demonstrated how to easily construct 4×4 PD magic squares from 5 arbitrarily chosen numbers (which need not form an arithmetical sequence). This approach builds upon classical Indian mathematical traditions, particularly the systematic methods outlined by Nārāyaṇa Paṇḍita in his *Gaṇitakaumudī*.

The quadrilayered visualisation highlights the pivotal role of the core layer (Layer 2), formed by four arbitrarily chosen numbers, in completely determining the elements of all subsequent layers. It is indeed noteworthy that every cell of this magic square is essentially made up of the powerset of Layer 2. Additionally, our exploration to find the characteristic polynomial shows that this admits a remarkably simple and elegant form.

Acknowledgements The authors would like to thank the reviewer for offering some valuable suggestions which have made the paper more elegant in terms of using notations, as well as complete from a historical perspective. They also would like to place on record their sincere gratitude to the Ministry of Education (MoE), Government of India (GoI), for the generous support extended to them to carry out research activities on Indian science and technology by way of initiating the Science and Heritage Initiative (SandHI) at IIT Bombay. One of the authors (Varuneshwar Reddy) would like to thank GoI for the Prime Minister's Research Fellowship (PMRF). They would also like to thank Dr. Lalitha Sarma R for reading the manuscripts and giving constructive suggestions.

Author contributions All authors contributed significantly to the study. The literature survey and mathematical analysis were conducted by Varuneshwar Reddy Mandadi. The first draft of the manuscript was prepared by Varuneshwar Reddy Mandadi and Sooryanarayan D G. Ramasubramanian K reshaped, commented on, and got the manuscript to its final form. All authors read and approved the final manuscript.

Funding The authors would also like to express their unreserved gratitude to the Prime Minister's Research Fellowship (PMRF) granted by MoE to one of the authors. The authors are also very grateful to the History of Mathematics in India (HOMI) project of IIT Gandhinagar for the generous support extended to the authors to carry out various research activities in this domain.

Declarations

Conflict of interest The authors declare that there is no conflict of interest.

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