ENERGIES OF GRAPHS

SURVEY, CENSUS, BIBLIOGRAPHY

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Contents

1 Introduction

The concept of graph energy was invented in 1978 by one of the authors of the present book (I.G.). After a twenty-years delay, it was recognized as a topic suitable for mathematical research. Somewhere around the year 2000, numerous publications concerned with graph energy and its various variants began to appear. In recent years their number exceeds one per week, showing no sign of attenuation.

On the other hand, the time of I.G. is about to expire. Bearing this in mind, we found it purposeful to provide a selection of statistical data on the research of graph energies, together with an as-complete-as-possible bibliography.

2 Survey of Graph Energies

2.1 Prehistory

The total π-electron energy (E_π), as calculated by the simplest tight-binding approximation of the molecular orbital theory, appeared for the first time in the early 1930s, in Erich Hückel's seminal paper "*Quantentheoretische Beiträge zum Benzolproblem I. Die Elektronenkonfiguration des Benzols und verwandter Verbindungen*" [1]. There he showed that the π-electron energy levels in benzene are

$$\begin{aligned} E_1 &= \alpha + 2\beta \\ E_2 &= \alpha + \beta \\ E_3 &= \alpha + \beta \\ E_4 &= \alpha - \beta \\ E_5 &= \alpha - \beta \\ E_6 &= \alpha - 2\beta \end{aligned}$$

with α and β being constants, representing, respectively, the Coulomb integral pertaining to a carbon atom and the carbon–carbon resonance integral; β is a negative–valued quantity. The total energy of the six π-electrons in benzene is thus

$$E_\pi(benzene) = 2\,E_1 + 2\,E_2 + 2\,E_3 = 6\alpha + 8\beta\,.$$

The importance of this result lies in the fact that the total π-electron energy of an isolated carbon–carbon double bond is equal to $E_\pi(C=C) = 2\alpha + 2\beta$. Therefore,

$$E_\pi(benzene) - 3\,E_\pi(C=C) = 2\beta$$

is the energy gain resulting by cyclic delocalization of three double bonds, understood to be the resonance energy of benzene and responsible for its aromaticity.

The method that eventually became known as the Hückel molecular orbital (HMO) theory enabled a reasonably accurate quantitative prediction of thermodynamic properties, resonance stabilization, and aromaticity of conjugated polycyclic π-electron systems

and gained much popularity in the next 50 years [2]. Most of the works in which the HMO total π-electron energy was considered were concerned with the calculation and applications of various resonance energies [3–6].

The connection between HMO theory and spectral graph theory is a well established and fully elaborated part of chemical graph theory [7–9]. If the eigenvalues of a molecular graph (of a conjugated π-electron system) are labeled as λ_i , $i = 1, 2, \ldots, n$, assuming that

$$\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n$$

then the energy of the i-th molecular orbital is

$$E_i = \alpha + \lambda_i \, \beta \, .$$

Within the HMO approximation, the total π-electron energy of an uncharged conjugated hydrocarbon is

$$E_\pi = \sum_{i=1}^{n} g_i \, E_i = \sum_{i=1}^{n} g_i (\alpha + \lambda_i \, \beta) = n\alpha + \beta \sum_{i=1}^{n} g_i \, \lambda_i$$

where g_i is the number of π-electrons in the i-th molecular orbital, and n the number of vertices of the underlying molecular graph. For such molecules in their ground electronic state, if n is even, then

$$g_i = \begin{cases} 2 & \text{if} \quad i = 1, 2, \ldots, n/2 \\ 0 & \text{if} \quad i = n/2 + 1, n/2 + 2, \ldots, n \end{cases}$$

whereas if n is odd, then

$$g_i = \begin{cases} 2 & \text{if} \quad i = 1, 2, \ldots, (n-1)/2 \\ 1 & \text{if} \quad i = (n+1)/2 \\ 0 & \text{if} \quad i = (n+1)/2 + 1, (n+1)/2 + 2, \ldots, n \, . \end{cases}$$

Consequently,

$$E_\pi = \begin{cases} n\alpha + 2\beta \sum\limits_{i=1}^{n/2} \lambda_i & \text{if} \quad n \text{ is even} \\ \\ n\alpha + 2\beta \sum\limits_{i=1}^{(n-1)/2} \lambda_i + \beta \, \lambda_{(n+1)/2} & \text{if} \quad n \text{ is odd} \, . \end{cases}$$

The only non-trivial part of this expression is what formally is obtained by setting $\alpha = 0$ and $\beta = 1$, usually referred to as the total π-electron energy in β-units:

$$E_\pi = \begin{cases} 2 \sum\limits_{i=1}^{n/2} \lambda_i & \text{if} \quad n \text{ is even} \\ \\ 2 \sum\limits_{i=1}^{(n-1)/2} \lambda_i + \lambda_{(n+1)/2} & \text{if} \quad n \text{ is odd} \, . \end{cases} \tag{1}$$

It was evident that mathematicians would hardly ever be interested to study a graph–spectrum–based quantity equal to the right–hand side of Eq. (1). Therefore, in order to make total π-electron energy more attractive to the mathematical community, one of the present authors made in 1978 a seemingly absurd and scientifically risky step, and proposed that instead of Eq. (1), attention be paid to the quantity defined as

$$E(G) = \sum_{i=1}^{n} |\lambda_i| \tag{2}$$

which he named graph energy [10], and which would be defined for any graph G.

The idea to define $E(G)$ as in Eq. (2) and to name it "energy" had the following chemical justification. The eigenvalues of many molecular graphs satisfy the condition

$$\begin{aligned} &\lambda_{n/2} \geq 0 \geq \lambda_{n/2+1} \quad \text{if} \quad n \text{ is even} \\ &\lambda_{(n+1)/2} = 0 \qquad\quad \text{if} \quad n \text{ is odd}\,. \end{aligned} \tag{3}$$

In the 1970s this was a well known fact. Conditions (3) hold for all bipartite graphs, which include benzenoid systems and trees, but hold also for a large number of non-bipartite species. For such graphs, recalling that the sum of all eigenvalues is equal to zero, it is elementary to verify the following:

Proposition 2.1. *If conditions (3) are obeyed, then the total π-electron energy, Eq. (1) is equal to the right–hand side of Eq. (2). In other words, the graph energy coincides with the HMO total π-electron energy (in β-units) if and only if the conditions (3) hold.*

The (implicit) awareness of Proposition 2.1 can be recognized in the works of Charles Coulson [11], George Hall [12], Klaus Ruedenberg [13], Bernard McClelland [14], and probably other pioneers of HMO theory. While studying HMO theory, one of the present authors noticed that two important earlier discovered results, namely Coulson's integral formula [11] and McClelland's inequality [14] hold if and only if the conditions (3) are satisfied. In other words, the actual results of Coulson and McClelland were the following two results:

Proposition 2.2. *Let G be an arbitrary graph with n vertices, let $\phi(G, \lambda)$ be its characteristic polynomial, and $i = \sqrt{-1}$. Then Coulson's expression* [11]

$$\frac{1}{\pi} \int_{-\infty}^{+\infty} \left[n - \frac{ix\,\phi'(G, ix)}{\phi(G, ix)} \right] dx$$

is equal to energy of any graph G, and coincides with the HMO total π-electron energy if and only if conditions (3) hold.

Proposition 2.3. *Let G be an arbitrary graph with n vertices and m edges. Then McClelland's expression* [14]

$$\sqrt{2mn}$$

is an upper bound for the energy of any graph G, and is an upper bound for the HMO total π-electron energy if the conditions (3) hold.

The observations stated above as Propositions 2.2 and 2.3 were the prime motivation to move from the mathematically repelling expressions (1) for HMO total π-electron energy to the much simpler expression (2). By means of this change, the previous HMO results (i.e., Coulson's formula [11] and McClelland's inequality for E_π [14]) would anyway remain valid for the vast majority (but not all!) chemically interesting cases. It is worth noting that E_π coincides with $E(G)$ for all alternant systems (including acyclic and benzenoid), but differs from $E(G)$ in the case of fullerenes and the majority of nanotubes.

Additional mathematical reasons for defining graph energy via Eq. (2) are outlined in the next subsection.

2.2 Ordinary graph energy

The first paper in which graph energy was defined as the sum of absolute values of the eigenvalues of the (0,1)-adjacency matrix of a graph G, namely as Eq. (2), appeared in 1978 [10]. It was published (in English language) in a difficult-to-find journal whose full title is *Berichte der Mathematisch–Statistischen Sektion im Forschungszentrum Graz*. The paper [10] is based on a series of lectures held by the author on a graph–theoretical conference in Stift Rein, Austria, in 1978. This article has been reproduced as an appendix in the paper [15].

As explained in the preceding subsection, the idea to define $E(G)$ as in Eq. (2) and to name it "*energy*" comes from quantum chemistry. However, there were other mathematical arguments for doing so. These are the following:

1) The right–hand side of Eq. (2) is independent of the labeling of graph eigenvalues, i.e., the graph energy is a *symmetric function* of graph eigenvalues. By this, graph energy belongs among the algebraically much studied symmetric functions.

2) Formula (2) is well defined for all graphs, and thus can be applied to all graphs, without the (mathematically frustrating) restriction to molecular graphs. This gives full

freedom to researchers, and enables them to arrive at results unimaginable to those thinking in terms of "molecular graphs".

3) By introducing the concept of graph energy, Eq. (2), the author of [10] hoped that it will attract the attention of "pure" mathematicians, and that the Coulson and McClleland formulas are just the first in a long series of exact and non-trivial mathematical results for $E(G)$, awaiting to be discovered in the future. This indeed happened, but more than a quarter-of-century later.

More details along these lines can be found in the book [16].

Already before the publication of [10], a few results that pertain to the energy of trees were obtained [17]. Paper [10] was followed by several attempts to popularize the graph–energy concept (e.g., on pp. 137–139 in the book [8], as well as [18]), but the mathematical and mathematico–chemical community remained uninterested until the beginning of the 21-st century. The only exception was the Chinese mathematician Fuji Zhang (see, for instance, [19, 20]).

Around year 2000 a dramatic change happened, and almost suddenly a large number of colleagues, from unrelated and geographically very distant places, started to study graph energy. It may be that a conference lecture, later published as [21], triggered this fortunate turn. In addition to [21], several additional review articles on graph energy were published [15, 22–24], as well as a book [25].

Nowadays, the number of publications concerned with graph energy and its various modifications is exceeding one thousand. Details on these research activities are found in the later parts of our book.

2.3 More graph energies

The graph energy $E(G)$, Eq. (2), is based on the eigenvalues of the ordinary adjacency matrix $\mathbf{A} = \mathbf{A}(G)$. Recall that for a graph G whose vertices are labeled by $v_1, v_2, \ldots, v_n$, $\mathbf{A}$ is a symmetric square matrix of order n whose (i, j)-element is defined as

$$\begin{cases} 1 & \text{if} \quad v_i \text{ and } v_j \text{ are adjacent} \\ 0 & \text{if} \quad v_i \text{ and } v_j \text{ are not adjacent} \\ 0 & \text{if} \quad v_i = v_j \, . \end{cases}$$

The mathematical examination of $E(G)$ resulted in scores of newly established properties and, consequently, in scores of published papers. In view of this success, a natural

idea was to look for some variants of graph energy that would also provide a basis for prolific mathematical researches.

The most obvious step in this direction was to employ eigenvalues of another well studied graph matrix. The most obvious candidate for this was the Laplacian matrix $\mathbf{L} = \mathbf{L}(G)$, defined as $\mathbf{L} = \mathbf{D} - \mathbf{A}$, where

$$\mathbf{D} = \mathbf{D}(G) = \begin{bmatrix} \deg(v_1) & 0 & 0 & \cdots & 0 \\ 0 & \deg(v_2) & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & \deg(v_n) \end{bmatrix}$$

and where $\deg(v_i)$ denotes the degree (= number of first neighbors) of the vertex v_i , $i = 1, 2, \ldots, n$.

Let the eigenvalues of $\mathbf{L}(G)$ be $\mu_1, \mu_2, \ldots, \mu_n$. Then, in analogy with Eq. (2), one could conceive the Laplacian energy of the graph G as

$$LE!(G) = \sum_{i=1}^{n} |\mu_i| \, .$$

However, because all Laplacian eigenvalues are non-negative, and because their sum is equal to $2m$, we would arrive at the trivial result $LE!(G) = 2m$. The way out of this difficulty was found in 2006 by defining the Laplacian energy as [26]

$$LE(G) = \sum_{i=1}^{n} \left| \mu_i - \frac{2m}{n} \right|$$

where m is the number of edges of the graph G. In other words, the Laplacian energy is the energy of the matrix $\mathbf{L} - \frac{2m}{n} \mathbf{I}_n$, where $\mathbf{I}_n$ stands for the unit matrix of order n.

The Laplacian energy was the first in a long series of energies based on other graph matrices. It was followed by the distance energy (based on the eigenvalues of the distance matrix), signless Laplacian energy (based on the eigenvalues of the signless Laplacian matrix, $\mathbf{D} + \mathbf{A}$), normalized Laplacian energy (based on the eigenvalues of the normalized Laplacian matrix $\mathbf{D}^{-1/2} \mathbf{L} \mathbf{D}^{-1/2}$), resistance–distance or Kirchhoff energy (based on the eigenvalues of the resistance–distance matrix), etc; details are found in the next section. Consonni and Todeschini [27] defined the energy of any real symmetric matrix with eigenvalues $\xi_1, \xi_2, \ldots, \xi_n$ as

$$E_{CT} = \sum_{i=1}^{n} \left| \xi_i - \frac{S}{n} \right|$$

where $S = \xi_1 + \xi_2 + \cdots + \xi_n$.

Much earlier, in 1994, Yang, Xu and Hu [28] introduced a so-called extended energy, the energy of the matrix whose (i,j)-element is

$$\begin{cases} \frac{1}{2}\left(\frac{\deg(v_i)}{\deg(v_j)} + \frac{\deg(v_j)}{\deg(v_i)}\right) & \text{if} \quad v_i \text{ and } v_j \text{ are adjacent} \\ 0 & \text{if} \quad v_i \text{ and } v_j \text{ are not adjacent} \\ 0 & \text{if} \quad v_i = v_j \, . \end{cases}$$

Their idea seems to came too early and was completely ignored by other scholars. The next paper on the same graph energy appeared only in 2017 [29].

Let $\mathcal{E}(G)$ denote the edge set of the graph G, and let ij stands for an edge connecting the vertices v_i and v_j. An often used method for designing new graph energies is to start from an earlier introduced topological index of the form

$$TI(G) = \sum_{ij \in \mathcal{E}(G)} f(v_i, v_j) \, .$$

Based on the above formula, one defines the matrix $\mathbf{M}_{TI} = (m_{ij})$ as

$$m_{ij} = \begin{cases} f(v_i, v_j) & \text{if the vertices } v_i \text{ and } v_j \text{ are adjacent} \\ 0 & \text{otherwise.} \end{cases}$$

The respective energy is then the sum of absolute values of the eigenvalues of $\mathbf{M}_{TI}$. An outstanding example is the Randić energy [30], pertaining to the choice

$$f(v_i, v_j) = \frac{1}{\sqrt{\deg(v_i) \, \deg(v_j)}} \, .$$

It is worth noting that the Randić energy and the normalized Laplacian energy coincide [30, 31].

Other graph energies of the same kind are the first and second Zagreb energy [32] and a whole series of recently conceived energies related to degree–based topological indices [33]. More details are found in the next section.

A major step forward in the theory of graph energies was done by Nikiforov [34], who extended the energy–concept to any matrix. If $\mathbf{M}$ is a $p \times q$ matrix (where p and q need not be equal), then the positive square roots of the eigenvalues of $\mathbf{M}\,\mathbf{M}^t$ are the singular values of $\mathbf{M}$. Their sum is defined as the energy of the matrix $\mathbf{M}$. In the case of real and symmetric (square) matrices, the new and the old energy–concepts coincide.

The first non-square matrix to which Nikiforov's concept was applied was the incidence matrix, resulting in the incidence energy $IE(G)$ [35]. Short time earlier, Liu and Liu [36]

introduced the so-called Laplacian–energy–like invariant, defined as

$$LEL(G) = \sum_{i=1}^{n} \sqrt{\mu_i}\,.$$

From a formal point of view, LEL is not a graph energy. However, it was soon discovered [37] that for bipartite graphs, $LEL(G) = IE(G)$, whereas in the general case (including non-bipartite graphs),

$$IE(G) = \sum_{i=1}^{n} \sqrt{\mu_i^+}$$

where $\mu_1^+, \mu_2^+, \ldots, \mu_n^+$ are the eigenvalues of the signless Laplacian matrix.

A subset $\mathcal{D}$ of the vertex set $\mathcal{V}$ of the graph G is said to be a dominating set of G if every vertex of $\mathcal{V} \setminus \mathcal{D}$ is adjacent to some vertex in $\mathcal{D}$. Any dominating set with minimum cardinality is said to be a minimum dominating set. The minimum dominating adjacency matrix of G is the $n \times n$ matrix whose (i, j)-element is

$$\begin{cases} 1 & \text{if the vertices } v_i \text{ and } v_j \text{ are adjacent} \\ 1 & \text{if } i = j \text{ and } v_i \in \mathcal{D} \\ 0 & \text{otherwise.} \end{cases}$$

Then the minimum dominating energy is defined as the sum of the absolute values of the eigenvalues of the minimum dominating adjacency matrix [38].

Eventually, numerous other "minimum dominating" energies as well and analogous "minimum covering" energies have been introduced; details are found in the subsequent section.

Let $\mathbf{M}$ be a square matrix of order n. In linear algebra, the resolvent matrix $\mathbf{R}_{\mathbf{M}}(z)$ of $\mathbf{M}$ plays an important role. It is defined as

$$\mathbf{R}_{\mathbf{M}}(z) = \big(z\,\mathbf{I}_n - \mathbf{M}\big)^{-1}\,.$$

Thus, $\mathbf{R}_{\mathbf{M}}(z)$ is also a matrix of order n, that exists for all values of z except when z coincides with an eigenvalue of $\mathbf{M}$.

In particular, the resolvent matrix of the adjacency matrix $\mathbf{A}$ of the graph G is

$$\mathbf{R}_{\mathbf{A}}(z) = \big(z\,\mathbf{I}_n - \mathbf{A}\big)^{-1}$$

and its eigenvalues are

$$\frac{1}{z - \lambda_i}\ ,\ i = 1, 2, \ldots, n\,.$$

Then, in analogy with Eq. (2), one could think of defining a "resolvent graph energy" as

$$\sum_{i=1}^{n} \left| \frac{1}{z - \lambda_i} \right|$$

that would then depend on the complex variable z and would not exist for $z = \lambda_i$, $i = 1, 2, \ldots, n$.

In order to ameliorate the above ill-defined "resolvent–energy" concept, taking into account that that the condition $\lambda_i \leq n - 1$ is satisfied by all eigenvalues of all n-vertex graphs, the choice $z = n$ was proposed [39].

Resolvent energies could be defined for any other matrix. Until now, this has been done only for the Laplacian, signless Laplacian, and normalized Laplacian matrices [40, 41].

2.4 The graph energy deluge

In the preceding subsection we briefly outlined some of the most relevant and most widely examined graph energies. There exist countless possibilities to associate a matrix to a graph [42]. For each such matrix, an "energy" and a "resolvent energy" could be constructed. In addition, an "energy" can be associated with any particular polynomial. Among such polynomial–based energies the "matching energy" plays an outstanding role [43]. In an implicit manner, this energy was conceived already in the 1970s [44, 45] and played role as a component of the so-called "topological resonance energy".

In the last few years, we are witnesses of an enormous increase of the number of various graph energies (by scholars the majority of whom is from India). These novel "graph energies" are introduced ad libitum, without any visible scientific justification. This phenomenon may be referred to as the "graph energy deluge", and should be viewed as a pathological feature of contemporary Mathematical Chemistry. In our records, we have data on well over a hundred fifty different graph energies. In what follows, we give a list thereof, with reference to the place where these have been considered for the first time. In reality, the number of existing graph energies may be still greater, and more such will for sure appear in the future.

By saying that the following list represents a "pathological feature of mathematical chemistry", the authors have expressed their personal critical opinion on this matter. On the other hand, the fact that the mentioned variants of graph energy do exist, cannot be and should not be ignored. The possibility that for some of these graph energies interesting and non-trivial mathematical properties will be discovered, or that some of these will find

application in some area of science or engineering should also not be disregarded. Anyway, a critical analysis of the advantages/disadvantages of the various "graph energies" has not been done so far. There is little doubt that in most cases, the authors proposing such graph invariants have taken neither any trouble to motivate the introduction of their new quantities, nor to find at least one application thereof.

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3 List of Hitherto Proposed Graph Energies

1	(ordinary) graph energy	[1]
2	extended adjacency energy	[2]
3	Laplacian energy	[3]
4	energy of matrix	[4]
5	minimum robust domination energy	[5]
6	energy of set of vertices	[6]
7	distance energy	[7]
8	Laplacian–energy–like invariant	[8]
9	Consonni–Todeschini energies	[9]
10	energy of $(0,1)$-matrix	[10]
11	incidence energy	[11]
12	maximum degree energy	[12]
13	skew Laplacian energy	[13]
14	oriented incidence energy	[14]
15	skew energy	[15]
16	Randić energy	[16]
17	normalized Laplacian energy	[17]
18	energy of matroid	[18]
19	energy of polynomial	[19]
20	Harary energy	[20]
21	sum-connectivity energy	[21]
22	second–stage energy	[22]
23	signless Laplacian energy	[23]
24	PI energy	[24]
25	Szeged energy	[25]
26	He energy	[26]
27	energy of orthogonal matrix	[27]
28	common-neighborhood energy	[28]
29	matching energy	[29]
30	Seidel energy	[30]
31	ultimate energy	[31]
32	minimum-covering energy	[32]
33	resistance-distance energy	[33]
34	Kirchhoff energy	[34]
35	color energy	[35]
36	normalized incidence energy	[36]
37	Laplacian distance energy	[37]
38	Laplacian incidence energy	[38]
39	Laplacian minimum dominating energy	[39]
40	minimum-domination energy	[40]
41	minimum-covering distance energy	[41]
42	degree sum energy	[42]
43	terminal distance	[43]
44	domination energy	[44]
45	general Randić energy	[46]

46	Randić incidence energy	[45]
47	Laplacian minimum-covering energy	[47]
48	minimum-dominating distance energy	[48]
49	e-energy	[49]
50	n-energy	[49]
51	double dominating energy	[50]
52	minimum-covering Harary energy	[51]
53	Hermitian energy	[52]
54	minimum hub distance energy	[53]
55	minimum monopoly energy	[54]
56	minimum monopoly distance energy	[55]
57	complementary dominating energy	[56]
58	upper dominating energy	[57]
59	minimum-maximal-domination energy	[58]
60	minimum-covering color energy	[59]
61	α-distance energy	[60]
62	α-incidence energy	[60]
63	so-energy	[61]
64	color Laplacian energy	[62, 63]
65	reciprocal complementary distance energy	[64]
66	non-common neighborhood energy	[65]
67	partition energy	[66]
68	minimum equitable dominating energy	[67]
69	minimum equitable color dominating energy	[68]
70	Nikiforov energy	[69]
71	resolvent energy	[70]
72	Laplacian resolvent energy	[71]
73	signless Laplacian resolvent energy	[71]
74	skew Randić energy	[72]
75	geometric–arithmetic energy	[73]
76	minimum hub energy	[74]
77	(two) reduced color energies	[75]
78	o-energy	[76]
79	peripheral distance energy	[77]
80	Co-PI energy	[78]
81	Coxeter energy	[79]
82	minimum dominating maximum degree energy	[80]
83	minimum covering Seidel energy	[81]
84	complementary distance energy	[82]
85	additive color Laplacian energy	[83]
86	maximum eccentricity energy	[84]
87	vertex degree energy	[85]
88	net-Laplacian energy	[86]
89	Laplacian partition energy	[87]
90	Hermitian–Randić energy	[88]

91	degree subtraction energy	[89]
92	minimum dominating Randić energy	[90]
93	eccentric Laplacian energy	[91]
94	distance signless Laplacian energy	[92]
95	ABC energy	[93]
96	iota energy	[94]
97	minimum boundary dominating energy	[95]
98	Laplacian minimum boundary dominating energy	[95]
99	minimum-dominating Harary energy	[96]
100	terminal distance energy	[97]
101	minimum covering Randić energy	[98]
102	color signless Laplacian energy	[99]
103	degree product energy	[100]
104	vertex Zagreb adjacency energy	[101]
105	forgotten energy	[101]
106	harmonic energy	[101]
107	path energy	[102]
108	extended signless Laplacian energy	[103]
109	Zagreb energies	[104]
110	inverse sum indeg energy	[105]
111	Seidel Laplacian energy	[106]
112	Seidel signless Laplacian energy	[107]
113	sum-eccentricity energy	[108, 109]
114	Laplacian sum-eccentricity energy	[110]
115	symmetric division deg energy	[111]
116	another version of Randić energy	[112]
117	reciprocal Randić energy	[112]
118	reciprocal sum-connectivity energy	[112]
119	arithmetic–geometric energy	[112]
120	inverse sum indeg energy	[112]
121	general sum-connectivity energy	[112]
122	Albertson energy	[112]
123	average degree-eccentricity energy	[113]
124	minimum equitable dominating Randić energy	[114]
125	edge-Zagreb energy	[115]
126	minimum total edge dominating energy	[116]
127	total energy of digraph	[117]
128	minimum edge covering energy	[118]
129	energy of vertex	[119]
130	Laplacian minimum-covering color energy	[120]
131	Laplacian minimum-covering chromatic energy	[120]
132	reciprocal distance signless Laplacian energy	[121]
133	energy of semigraph	[122]
134	intrinsic energy	[123]
135	greatest common divisor energy	[124]

136	greatest common divisor degree energy	[125]
137	complement Randić energy	[126]
138	minimum edge dominting energy	[127]
139	normalized Laplacian resolvent energy	[128]
140	average degree energy	[129]
141	generalized distance energy	[130]
142	complementary distance signless Laplacian energy	[131]
143	minimum covering Gutman energy	[132]
144	minimum paired dominating energy	[133]
145	degree equitable connected cototal dominating energy	[134]
146	connected complement domination energy	[135]
147	minimum dom strong dominating energy	[136]
148	minimum mean dominating distance energy	[137]
149	minimum mean boundary dominating energy	[138]
150	minimum covering reciprocal distance signless Laplacian energy	[139]
151	accurate independent dominating energy	[140]
152	first Hermitian–Zagreb energy	[141]
153	minimum maximal domination energy	[142]
154	maximum independent vertex energy	[143]
155	minimum dominating Seidel energy	[144]
156	edge-energy	[145]
157	detour energy	[146]
158	extended ABC energy	[147]
159	inverse dominating energy	[148]
160	minimum dominating partition energy	[149]
161	minimum *bb*-dominating energy	[150]
162	arithmetic–geometric energy	[151]
163	rational metric energy	[152]
164	degree subtraction adjacency energy	[153]
165	Randić color energy	[154]
166	path Laplacian energy	[155]
167	minimum efficient dominating energy	[156]
168	minimum Laplacian efficient dominating energy	[157]
169	minimum majority domination energy	[158]
170	minimum mean dominating energy	[159]
171	minimum neighborhood energy	[160]

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4 Census of Graph Energies

Somewhere around the year 2007, the number of publications on graph energy started to significantly increase. This trend is illustrated in Table 1 and Figure 1 where the distribution of graph–energy–papers by years in the last two decades are shown.

year	#pap.	comment	year	#pap.	comment
1996	2		2008	57	> o.p.w.
1997	0		2009	72	> o.p.w.
1998	2		2010	69	> o.p.w.
1999	6		2011	61	> o.p.w.
2000	4		2012	63	> o.p.w.
2001	12		2013	63	> o.p.w.
2002	3		2014	76	> o.p.w.
2003	5		2015	114	> t.p.w.
2004	9		2016	113	> t.p.w.
2005	16		2017	132	> t.p.w.
2006	11		2018	112	> t.p.w.
2007	35		2019	63	as on May 1

Table 1: Number of published works on graph energies that appeared around year 2000 and later, a total of over 1000 papers. In the last few years, such papers were produced faster than one per week (= o.p.w.) or two per week (= t.p.w.). Based on these data, an attenuation of this speed is not to be expected in the foreseen future. The authors are aware that there must be numerous additional papers published in India and China (in particular, those in Chinese language) that are not accounted for.

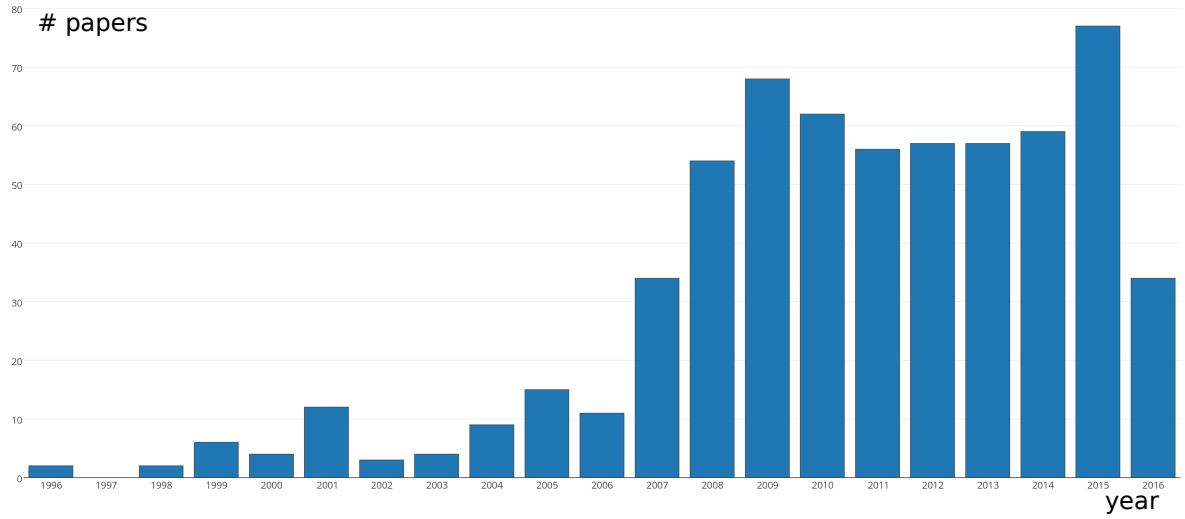

Figure 1: Distribution of the published graph energy papers by years.

Table 2 and Figures 2 and 3 show the distribution of authors of graph–energy–papers by the country of affiliations. In Figure 2 is shown a world map indicating the countries in which these authors were employed, when creating their graph–energy articles. Figure 3 indicates the relative number of authors who were publishing graph–energy–papers by their affiliation's countries.

country	no.	country	no.	country	no.	country	no.
Argentina	6	Georgia	1	Mexico	7	Slovenia	4
Australia	6	Germany	11	Morocco	1	South Africa	5
Austria	3	Greece	2	Norway	1	South Korea	15
Bahrain	1	Hungary	2	Netherlands	5	Spain	2
Belgium	2	India	260	Oman	4	Sweden	1
Brazil	16	Indonesia	8	Pakistan	25	Taiwan	4
Canada	9	Iran	89	Philippines	3	Thailand	3
Chile	16	Ireland	1	Poland	3	Turkey	23
China	267	Israel	1	Portugal	3	UK	10
Colombia	12	Italy	15	Romania	5	Uruguay	2
Croatia	4	Japan	4	Russia	1	USA	66
Czechia	1	Kuwait	7	Saudi Arabia	6	Venezuela	8
Ethiopia	1	Lebanon	1	Serbia	39		
Finland	2	Malaysia	15	Singapore	2		
France	8	Malta	4	Slovakia	2		

Table 2: Number of scholars from various countries who authored or coauthored at least one article on graph energy in the period 1996–2019 (as on May 1, 2019). Their true count is somewhat greater because we did not distinguish between scholars with the same surname and different names beginning with the same letter. Thus, Xia Li, Xuechao Li, and Xueliang Li were counted as one. Note that all continents, with the regretful exception of Antarctica, are represented in this field of research.

In what follows are the names of scholars (known to us) who authored at least one paper or book on graph energies.

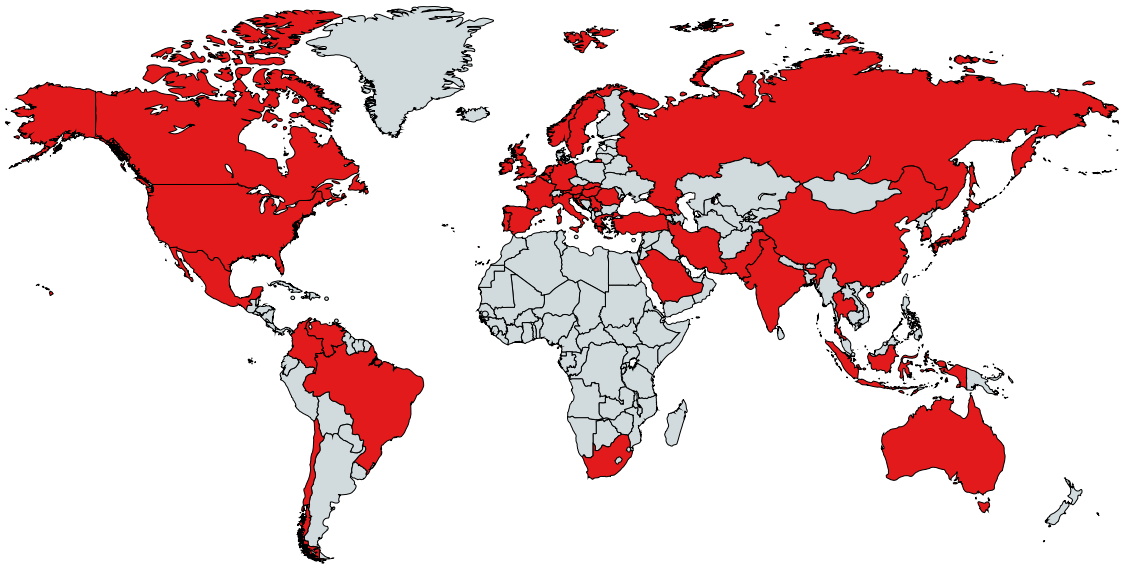

Figure 2: Countries where researches on graph energy were conducted.

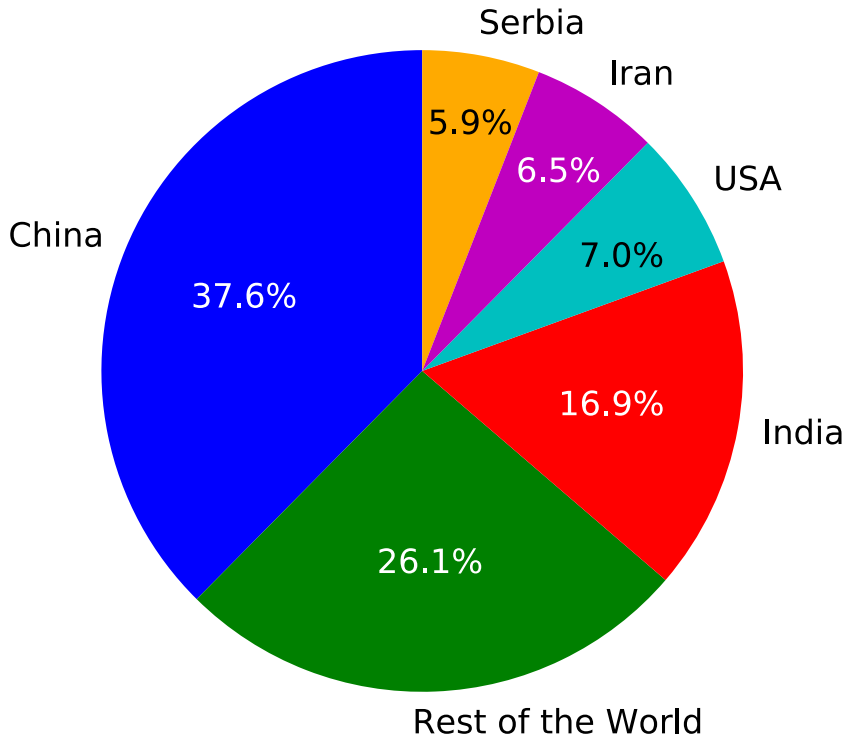

Figure 3: Relative number of authors by countries where they have been working in the time when their graph–energy articles were produced. This pie-chart emphasizes countries where the percentage of authors is greater than 5% .

Argentina

A. Cafure, L. N. Grippo, D. A. Jaume, E. Musulin, A. Pastine, M. D. Safe

Australia

S. R. Blackburn, B. Rajan, I. Shparlinski, S. Stephen, Z, Zhang, J. Zhou

Austria

M. Dehmer, C. Heuberger, S. Tripathi

Bahrain

A. K. Joseph

Belgium

A. Bultheel, H. Mélot

Brazil

N. M. M. de Abreu, L. E. Allem, A. S. Bonifácio, J. Capaverde, J. B. Carvalho, M. A. de Freitas, R. R. Del-Vecchio, E. Fritscher, C. Hoppen, D. A. R. Justo, L. Kowalski Pinheiro, G. Molina, I. Rocha, V. Trevisan, F. C. Tura, C. T. M. Vinagre

Canada

M. Aouchiche, G. Caporossi, M. Cavers, E. Chasset, S. Drury, S. Fallat, P. Hansen, N. Jahanbakht, H. Kharaghani

Chile

A. Soares Bonifácio, J. Carmona, R. Díaz, M. A. A. de Freitas, R. Jiménez, E. Lenes, E. Mallea–Zepeda, L. Medina, G. Pastén, M. Robbiano, J. Rodríguez Z., O. Rojo, B. San Martín, N. J. Tamblay, K. Tapia, E. Valero K.

China

M. Ajmal, J. Bai, X. Bai, Y. Bai, Q. Bian, J. Cai, Q. Cai, X. Cai, J. Cao, Y. Cao, A. Chang, A. Chen, H. Chen, H. M. Chen, J. Chen, L. Chen, R. S. Chen, W. Chen, X. Chen, Z. Chen, B. Cheng, J. Cheng, L. Chi, R. Chu, Z. Q. Chu, D. Cui, S. Y. Cui, W. Dang, Q. Diao, B. Deng, F. Deng, H. Deng, L. Dong, Q. D. Dong, W. Du, X. Du, Z. Du, C. Duan, X. Fai, X. Fang, L. Feng, M. Gao, N. Gao, X. Gao, Y. Gao, Z. Gao, Y. Ge, F. Gong, S. C. Gong, D. Guo, J. Gu, T. Gu, G. Guo, L. Guo, J. He, C. Hong, X. Hong, Y. Hou, D. Hu, M. Hu, X. Hu, H. Hua, F. Huang, G. Huang, Q. Huang, T. Z. Hunag, X. Hunag, Y. Huang, X. Hui, B. Huo, Y. Hou, S. Ji, Y. L. Jin, M. Jin, L. G. Jian, J. Jiang, H. Kan, Y. Kang, J. H. Koolen, M. Kuang, W. Lang, L. Lei, T. Lei, F. Li, G. Li, H. Li, H. H. Li, J. Li, N. Li, S. Li, W. Li, X. Li, X. X. Li, Y. Li, Z. Li, H. Lian, M. Lianq, M. Liao, A. Lin, H. Lin, W. Lin, X. Lin, B. Liu, C. Liu, H. Liu, J. Liu, J. B. Liu, L. Liu, M. Liu, Q. Liu, R. Liu, S. Liu, W. Liu, X. Liu, Y. Liu, Y. M. Liu, Z. Liu, Z. Lou, D. Q. Lu, H. Lu, H. Lü, L. Lu, M. Lu, X. Lu, Y. Lu, R. Luo, Y. Luo, B. Lv, D. Lv, X. Lv, G. Ma, H. Ma, T. Ma, X. Ma, H. Mao, Y. Mao, Z. Mu, B. Ning, J. Ou, X. Pai, X. F. Pan, Y. Pan, A. Peng, X. Qi, H. Qian, L. Qiao, Y. Qiao, S. Qin, Z. Qin, W. Qiu, M. U. Rehman, H. Ren, Q. Ren, S. Renqian, M. Riaz, H. Y. Shan, J. Y. Shao, Y. Shao, Z. Shao, L. Shen. P. Shen, X. Shen, L. Shi, Y. Shi, W. C. Shiu, Y. Sun, S. W. Tan, Y. Tang, Z. Tang, Q. Tao, Z. Teng, F. Tian, G. X. Tian, J. K. Tian, T. Tian, D. Wang, G. Wang, H. Wang, J. Wang, K. Wang, L. Wang, M. Wang, Q. A. Wang, W. Wang, W. H. Wang, X. Wang, Z. Wang, F. Wei, M. Wei, W. Wei, D. Wong, B. Woo, C. Woo, C. W. Woo, B. F. Wu, F. Wu, H. Wu, Q. Q. Wu, R. Wu, T. Wu, X. Wu, P. Xiao, C. Xie, J. Xie, B. Xu, Q. Xu, G. Xu, K. Xu, L. Xu, S. Xu, X. Xu, Y. Xu, Y. S. Xue, W. Yan, J. Yang, K. Yang, L. Yang, W. Yang, X. Yang,

Y. Yang, X. Yao, C. Ye, L. Ye, P. X. Ying, L. You, Z. You, A. Yu, G. Yu, L. Yu, R. Yu, Z. Yu, Z. S. Yu, X. Yuan, X. Y. Yuan, X. Zha, F. Zhan, B. Zhang, C. Zhang, F. Zhang, H. Zhang, J. Zhang, L. Zhang, R. Zhang, S. Zhang, W. Zhang, X. Zhang, X. D. Zhang, Y. Zhang, Z. Zhang, B. Zhao, H. Zhao, L. Zhao, M. Zhao, N. Zhao, P. Zhao, Q. Zhao, R. Zhao, H. Zheng, L. Zheng, L. J. Zheng, Z. Zheng, L. Zhong, W. B. Zhong, B. Zhou, H. Zhou, J. Zhou, Q. Zhou, Y. X. Zhou, J. Zhu, L. Zhu, X. Zhu, Y. Zhu, Z. Zhu, L. Zou

Colombia

N. Agudelo, C. A. M. Arango, D. Blázquez–Sanz, D. Bravo, R. Cruz, F. Cubría, H. Giraldo, E. Lenes, C. A. Marín, J. D. Monsalve, J. Rada, M. Rivera

Croatia

A. Graovac, A. Klobučar, S. Majstorović, N. Trinajstić

Czechia

M. Pokorný

Ethiopia

K. Venkatesa

Finland

F. Emmert–Streib, A. Musa

France

H. A. Bay–Ahmed, A. Bayad, A. O. Boudraa, E. Chasset,
D. Dare–Emzivat, O. Hammami, Q. A. Wang, Y. Zhu

Georgia

G. Lekishvili

Germany

M. Dehmer, C. Helmberg, J. H. Koolen, T. A. Le, W. Li, H. Richter,
M. A. Rostami, J. W. Sander, T. Sander, H. Täubing, J. Weihmann

Greece

N. Palla, I. Triantafillou

Hungary

A. Iványi, G. Y. Katona

India

B. D. Acharya, C. Adiga, M. Alatif, A. Alwardi,
J. Amreem, A. Amutha, K. Ananthi, S. A. Angadi, Ankayarkanni,
A. Anuradha, B. R. Arun Kumar, R. Arundhadhi, M. P. Ashawini,
K. Ashoka, S. K. Ayyaswamy, S. Aziz, S. Balachandran,
R. Balakrishnan, S. Balakrishnan, S. N. Banasode, R. B. Bapat,
S. A. Barde, B. Basavanagoud, V. Baths, A. Bayad, K. S. Betageri,
V. P. Bhamare, B. N. Bharmendra, N. Bhaskar, M. A. Bhat,
P. G. Bhat, R. S. Bhat, A. Bharali, K. A. Bibi, R. Binthiya, R. G. Boli,
B. Buzarboruah, M. V. Chakradhararao, M. G. Chandra, S. Chandra,
V. M. Chandrasekaran, B. A. Chat, S. Chattopadhyay,

A. V. Chithra, D. Cokilavany, S. Dalapati, K. C. Das, P. Das,
R. Das, A. Dasgupta, N. De, R. K. De, G. Deepa, K. Deepika,
V. Deshmukh, C. M. Deshpande, G. S. Devi, A. Dhanalakshmi,
B. N. Dharmendra, S. Dhivyakannu, A. C. Dinesh, B. R. Doddaman,
S. D'Souza, B. S. Durgi, J. Dutta, P. Dutta, S. Elumalai,
V. M. Gadag, Y. S. Gaidhani, H. A. Ganie, A. Gaur,
K. Gavirangiah, K. A. Germina, S. K. Giregol,
V. K. Govindan, S. Gowda, H. J. Gowtham, M. C. Gudgeri,
G. A. Gudodagi, M. M. Gundloor, G. A. Guodagi, S. B. Halkarni,
S. K. Hameed, P. R. Hampiholi, S. P. Hande, S. M. Hatture,
P. S. Hiremath, S. M. Hosamani, G. Indulal, R. Jagadeesh,
P. Jayalakshmi, G. Jenitha, S. P. Jeyakokila, S. R. Jog,
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H. N. Maraddi, V. Mathad, S. Mathew, J. Mayamma, K. Meenakshi,
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G. H. Mokashi, D. B. V. Murthy, K. B. Murthy, N. Murugesan,
K. Nagarajan, A. Nagarani, P. Nageswari, A. M. Naji, K. C. Nandeesh,
D. Naramatha, A. Narayanan, R. Naresh, R. K. Nath,
P. Naveen, L. Nayak, N. G. Nayak, S. S. Nayak,
S. R. Nayaka„ S. K. Nimbhorkar, P. Panigrahi, S. C. Patekar,
S. Pati, D. D. Patil, J. B. Patil, M. M. Patil, P. V. Patil,
V. Patil, B. Parvathalu, S. Paul, M. S. Paulraj,
I. Paulraj Jayasimman, P. Pavithra, M. M. Pawar, K. Perni,
R. S. Philipose, S. Pirzada, R. Poojary, K. M. Popat,
P. N. Pournami, B. Praba, R. Pradeep Kumar, O. Prakash,
Puttaswamy, K. N. Prakasha, N. B. R. Pratap, A. Raghavendra,
S. Raja, B. Rajagopal, K. Rajakumar, B. Rajan, J. K. Rajan,
M. A. Rajan, P. Rajendra, M. R. Rajesh Kanna, H. S. Ramane,
H. N. Ramaswamy, R. S. Ramkumar, R. A. Ramyashree,
K. Ranganathan, R. Rangarajan, P. S. Ranjini, V. Ramdos,
R. A. Ramyashree, K. S. Rao, M. V. C. Rao, S. B. Rao,
J. Ravi Sankar, L. C. Reddy, P. S. K. Reddy, D. S. Revankar,
S. V. Roopa, U. Samee, E. Sampathkumar, P. B. Sarasija, M. Saravanan,

M. D. Saroja, B. Satyanarayana, N. Selvi, V. M. Selvi, G. B. S. Shalini, B. Sharada, S. Sharief Basha, A. Sharma, U. Sharma, R. Shashi, V. S. Shigehalli, M. M. Shikare, S. D. Shindhe, S. S. Shirakol, B. W. Shwetha, V. M. Siddalingaswamy, T. Singh, K. Sivakumar, M. Smitha, P. Solairani, D. D. Somashekara, N. D. Soner, B. Sooryanarayan, M. I. Sowaity, M. A. Sriraj, G. Sridhara, S. A. Srinivas, S. Suganthi, P. Sumathi, Sumithra, R. Suresh, S. Suthar, V. Swaminathan, P. Tamilprabha, T. Tamizh Chelvam, P. Thirunavukarasu, S. Timmanaikar, S. Udupa, Y. M. Umathar, S. K. Vaidya, A. Varghese, T. K. M. Varkey, Varsha, C. R. Veena, K. A. Venkatesh, K. A. Vidya, B. Vidyapith, S. Vijay, A. Vijayakumar, B. Vijayalakshmi, R. Vijayaragavan, S. Vimala, H. B. Walikar, S. Yahya Mohamad, A. S. Yalnaik, R. K. Zaferani

Indonesia

Abdussakir, E. T. Baskoro, M. N. Jauhari, C. C. Marzuki, Muzakir, E. Susanti, Turmudi, N. M. Ulya

Iran

H. Abolghasemi, M. M. H. Aghaei, B. Ahmadi, M. R. Ahmadi, S. Akbari, M. H. Akhbari, A. Alhevaz, S. Alikhani, F. Alinaghipour, Y. Alizadeh, H. Aram, J. Asadpour, A. R. Ashrafi, Jalal Askari, S. M. Badadhe, Y. Bagheri, M. Baghipur, H. Bamdad, A. Banihashemi Dehkordi, R. A. Borzooei, N. Dehgardi, M. Einollahzadeh, A. Erfanian, M. Eslampour, M. Faghani, M. R. Farahani, G. H. Fath–Tabar, S. Fathi, H. Fatoorehchi, F. Fayazi, N. Ghanbari, Z. Gharavi–Alkhansari, Z. Gharavi–AlkhansariM. B. Ghaznavi–Ghouchi, H. Ghodrati, E. Ghorbani, M. Ghorbani, A. H. Hadian Rasanan, M. Hakimi–Nezhaad, E. Hashemi, S. Heidari–Rad, A. Heydari, M. A. Hosseinzadeh, M. A. Iranmanesh, S. H. Jafari, N. Jafari Rad, A. Jahanbani, R. Jahani–Nezhad, M. Jalali–Rad, M. R. Jooyandeh, B. A. Keshe, A. A. Khakpoor, M. M. Karkhaneei, F. Kashkooei Jahromi, D. Kiani, F. Koorepazan–Moftakhar, M. J. Mikmehr, M. Mirzakhah, F. Moazami, M. Moghaddam, F. Mohebi, R. Mojarad, F. Mohebbi,

M. Mollahajiaghaei, F. Movahedi, M. J. Nadjafi–Arani, M. Nasiri, M. A. Nematollahi, P. Nikzad, M. R. Oboudi, H. Panahbar, E. Pourhadi, H. Rashmanlou, H. H. Raz, S. Saadat Akhtar, S. Sabeti, F. Safaei, M. Safeli, S. M. Semnani, R. Sharafdini, S. R. Sharbaf, A. Shariatinia, B. Siamy, N. Soleimani, M. Songhori, S. Tabriz-Chi, B. Tayfeh–Rezaie, S. Zangi, S. Zare Firoozabadi

Ireland

S. Kirkland

Israel

F. Goldberg

Italy

M. Bertolaso, M. Bianchi, G. P. Clemente, V. Consonni, A. Cornaro, L. Di Paola, A. Di Venere, S. Filippi, A. Giuliani, G. Mei, E. Munarini, L. Piantedosi, R. Todeschini, A. Torriero, G. Zollo,

Japan

H. Hosoya, Y. Mizoguchi, K. K. K. R. Perera, K. Yuge

Kuwait

M. Anđelić, A. Bulut, M. Ghebleh, I. Hacioglu, A. Kanso, K. Kaskaloglu, D. Stevanović

Lebanon

B. Mourad

Malaysia

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