Viana, V., Nagy, D., Xavier, J., Neiva, A., Ginoulhiac, M., Mateus, L. & Varela, P. (Eds.). (2022). Symmetry: Art and Science | 12th SIS-Symmetry Congress [Special Issue]. *Symmetry: Art and Science*. International Society for the Interdisciplinary Study of Symmetry. 160-165. https://doi.org/10.24840/1447-607X/2022/12-20-160

FULLERENE-LIKE ARCHITECTURE OF POLLEN

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Rodriguez Padilla, A., …, Delusina, I., et al. (2021). Joint earthquake ruptures of the San Andreas and San Jacinto faults, California, USA. Geology; 50 (4): 387–391. https://doi.org/10.1130/G49415.1
Delusina, I. et al (2022). Environmental evolution of peat in the Sacramento – San Joaquin Delta (California) during the Middle and Late Holocene as deduced from pollen, diatoms, and magnetism. Quaternary International, V.621, 50-61. https://doi.org/10.1016/j.quaint.2020.05.012

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Katz, E. A., Jin, B.-Y. (2016). Fullerenes, Polyhedra and Chinese Guardian Lions. Mathematical Intelligencer, 38 (3), 61-68. https://doi.org/10.1007/s00283-016-9663-0
Katz, E. A. (2019). Leonardo’s Polyhedra with Solid Edges, Fullerenes and Skeletal Nanocages. The Israeli Chem-ist and Chemical Engineer, 5, 34-36. https://ice.digitaler.co.il/ice2019/36/

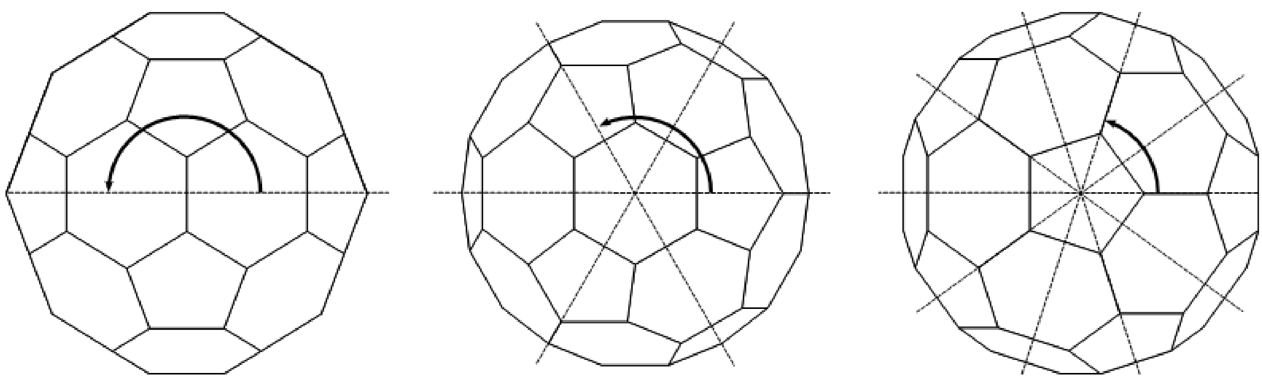
Abstract: *The paper presents observations of the similarity of external grain shape and symmetry characteristics of the internal structure of pollen and spore grains of plants with the molecular structure of fullerenes. It is suggested that the fullerene-like structures observed in sporopollenin-containing pollen and spores leads to minimization of the energy and matter resources of grains in their life span as well as maximizes their strength and pollination effectiveness.*

Keywords: Pollens and Spores; Fullerene; 5-Fold Symmetry; Sporopollenin; Exine

INTRODUCTION

The 1985 discovery of the C_{60} molecule, with carbon atoms at the 60 vertices of a truncated icosahedron (Kroto *et al*., 1985, pp.162-163) was an important event in the nanotechnology revolution. The discoverers named it *buckminsterfullerene*, after the American architect Buckminster Fuller. The now-famous family of *fullerenes* - molecules of pure carbon in the shape of convex polyhedra with degree-3 vertices and pentagonal and hexagonal faces - soon followed (Haymet, 1986, p.108). For any convex polyhedron with F faces, E edges, and V vertices, we have the Euler relation $V - E + F = 2$. It is easy to show that the faces cannot all be hexagons. For fullerenes, where f_6 and f_5 are the numbers of hexagonal and pentagonal faces, respectively, it is almost as easy to show that $f_5 = 12$ and $V = 2(10 + f_6)$. Thus, the number of pentagonal faces is always 12. The value of f_6 can be any number but 1 (Grünbaum and Motzkin, 1963). Accordingly, the smallest fullerene, C_{20}, has a shape of the regular dodecahedron, formed only by pentagons. Other fullerenes are C_{24}, C_{26}, C_{28}, …, C_{60}, C_{70}, $C_{2(10+h)}$… . In this context, the entire family of fullerene polyhedra can be considered as '*diluted dodecahedra*'. By dilution we understand here adding hexagonal faces to the dodecahedron skeleton.

According to group theory. the C_{60} structure (truncated icosahedron) belongs to the same point group of symmetry as the regular icosahedron and dodecahedron, I_h. This group of icosahedral symmetry includes the highest number of symmetry elements (120 elements) of all types: centre of symmetry (inversion centre), plains of mirror reflection (bilateral symmetry) and axes of *2*-, *3*- and *5*- fold rotational symmetry (Figure 1). Some fullerenes, though not all, also belong to the I_h group as well as to another icosahedral group *I*, without the centre of symmetry (Katz and Jin, 2016). None of such symmetrical molecules was known before the discovery of C_{60}. For our narrative, the presence of five-fold symmetry in such molecular structures is of special importance. Nature uses fullerene-like structures to minimizes energy and matter resources at various scales: nano (molecules and nanoclusters) and micro-scale (viruses, radiolarians, micro-algae, pollen and spores) (Katz, 2008, pp.173-189). In this paper, we address the fullerene-like structures in plants pollen and spores.



A B C

Figure 1 Axes of rotational symmetry in truncated icosahedron: A – two-fold axes, B – three-fold axes, C– five-fold axes (Katz & Jin, 2016).

WHAT ARE POLLEN AND SPORES?

Micro-scale pollen and spores (Figure 2) represent a "container" for preservation and transportation of plant genetic material.

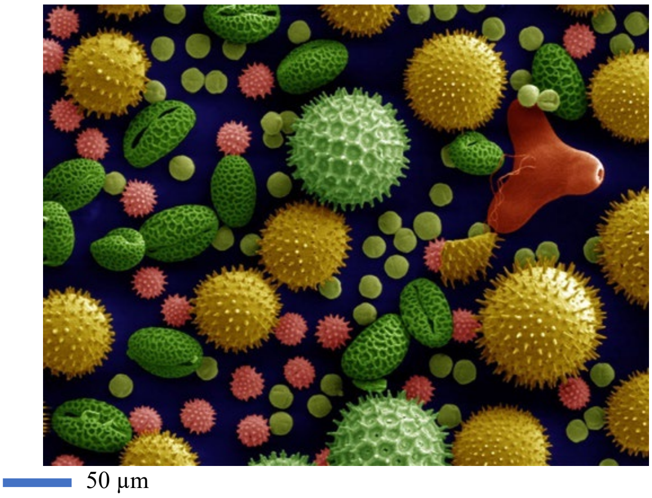
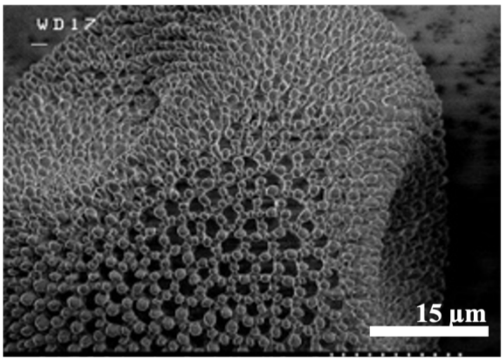


Figure 2 Pollen from a variety of common plants: sunflower (Helianthus annuus, small spiky sphericals, colorized pink), morning glory (*Ipomoea purpurea*, big sphericals with hexagonal cavities, colorized mint green), hollyhock (*Sildalcea malviflora*, big spiky sphericals, colorized yellow), lily (*Lilium auratum,* bean shaped, colorized dark green), primrose (*Oenothera fruticosa,* tripod shaped, colorized red) and castor bean (*Ricinus communis*, small smooth sphericals, colorized light green). Via Wikimedia Commons[1].

They are durable bodies of varying well-defined shapes formed in the male structures of seed-bearing plants and are key elements of the reproductive cycle. For fertilization, plants must be pollinated, and this is the main function of pollen. However, pollen and spores' reproductive times, and their life spans are millions of times shorter than the life of their extremely durable shells which are exceptionally resistant to any chemical and physical type of destruction. These shells have been preserved in sediments since plants emerged on the Earth more than 400 million years ago, even though other parts of a plant rarely survive in the fossil records. Pollen grains are known to develop a complex symmetry (Wodehouse, 1929: pp.342-344), and some of them exhibit fullerene-like ornaments on their walls *(exine*), and fullerene-like symmetry in positions of their structural elements such as spines (Andrade *et al*., 2014, p.1) and even a fullerene-like structure of the exines (Kedves *et al*., 2000, pp.186-188). In this paper we raise the question of why pollen grains exhibit these structural peculiarities and try to suggest certain answers.

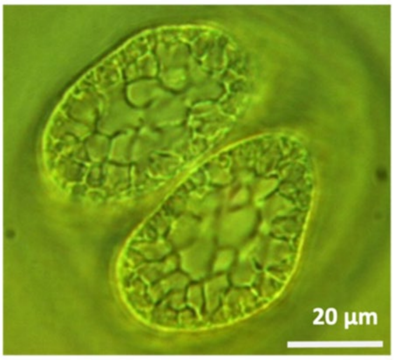
FUNCTION OF FULLERENE-LIKE SHAPE AND ORNAMENT OF POLLEN EXINE

The fern *Lycopodium clavatum* (clubmoss), which is pollinated by water, is one of the first terrestrial plants known and has been around for at least 400 million years. It produces spores with prominent fullerene-like wall ornaments (Figure 3). On the one hand, other pollen-producing plants, like conifers, which appeared 360 million years ago, have developed the ability to be pollinated by wind. *Pinus spp.* (Pine) exhibit a fullerene-like structure inside of their sacs (Figure 4: A-B), but not in their grain shape. Lycopods and conifers must produce an enormous number of spores and pollen grains.



A B

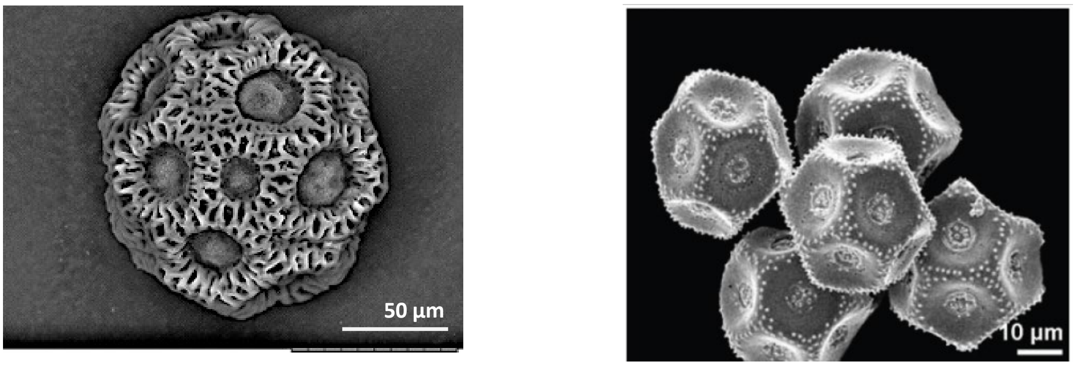
Figure 3 A: Light microscope image of Lycopodium clavatum (club moss); B: Scanning electron microscopy (SEM) image of Cercis occidentalis (western redbud), Fabaceae family. Segment of the exine, magnification x100. Represent fullerene-style ornament of the whole walls of pollen. Photos of authors.



A B

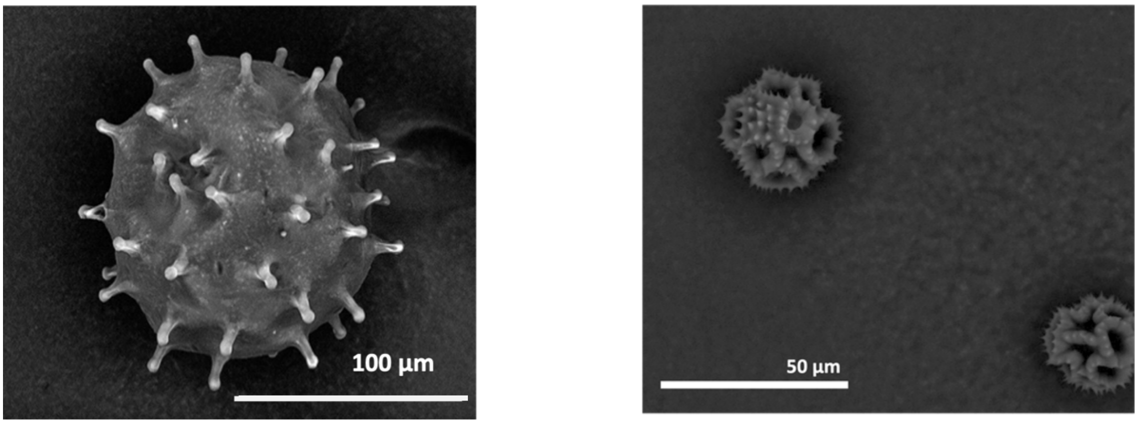
Figure 4 Light microscope images of *Pinus ponderosa* (ponderosa pine), Pinaceae family: A: magnification x20, B x100; these pollens show of fullerene-like appearance only on some of their parts. Photos of authors.

As an example of the resourcefulness of pollination, consider that to reach the female receptor, male conifers cones should produce about a million grains per square meter (Cowen, 2013; p.191). For the process to end successfully, pollen grains dispersed from the anther must be packed on the top of stigma, where the surface of contact between male and female grains must be optimal. The fullerene-like shape and configuration of pollen grain helps to achieve this process and plays an enormous role in it. Figure 5 and 6B represent pollen with pronounced fullerene-like external grain shape. The most interesting example is a grain with exact regular dodecahedron shape (Figure 5 B). In particular, the presence of five-fold symmetry in the grain shape does not allow their "close packing" and maximizes the "active" surface. On the other hand, fullerene-like shape also contributes to the pollen/spore strength. Water and wind pollination is possible only for tightly clustered plants, like lycopods or conifers. Plants growing individually need an assist that can be provided by insects. Primitive, late Jurassic Angiosperms (flowering plants) were the first insect-pollinated plants, and logically the morphology of their pollen became significantly different. Thus, plants have developed a pollen symmetry providing extreme resistance, which is particularly important for the more "economical" method of pollination by insects and birds. Andrade *et al*. (2014, p.3) demonstrated a clear correspondence between the positions of spines in the pollen grain of bird pollinated *Hibiscus sp.,* Malvaceae and those of atoms in a C_{60} molecule (vertices in the truncated icosahedron) (Figure 1). Our own SEM observations have confirmed this result (Figure 6 A).



A B

Figure 5 Scanning electron microscopy (SEM) of pollen with pronounced fullerene-like external grain shape, both pollinated by insects. A: Opuntia basilaris, *Cactaceae* family (photo of authors). B: *Stellaria holostea*, Caryophyllaceae family (from Halbritter and Auer, 2021, PalDat - Palynological Database[2]).



A B

Figure 6 A: Fullerene-like symmetry of spikes in the pollen grain of self- or bird pollinated *Hibiscus arnottianus* (Hawaiian White Hibiscus), *Malvaceae* family. B: Insect pollinated Taraxacum sp. (dandelion), Asteraceae family. Photos of authors.

SPOROPOLLENIN HYPOTHESIS

Pollen and spores are members of a larger group of entities named “palynomorphs”, united by their microscopic size and the existence of highly resistant parts that survive erosion and can be isolated and identified in geological deposits. In their walls, only some palynomorphs contain *sporopollenin,* a highly durable carbon/hydrogen/oxygen biopolymer configuration. Sporopollenin can be found in Acritarches, Dinoflagellates, some micro-Algae, and most pollen and spores. The sporopollenin-containing organisms listed above are the leaders in geological preservation (Zhu *et al*., 2021, p.1).

We hypothesize that they all have another common characteristic: during its synthesis sporopollenin builds a fullerene-like architecture into the final product, exine, which is not as obviously visible to researchers as the shape and ornament of the grains. Our proposal is supported by the discovery of the quasi-crystalline molecular structure of sporopollenin with the five-fold rotational symmetry (Kedves, 1989, see Figure 3, p. 65; and Kedves *et al.*, 2000).

CONCLUSION

Various observations allow us to infer that fullerene-like structure observed in sporopollenin-containing pollen and spores was developed during plant evolution to maximize the pollen strength and the pollination effectiveness.

REFERENCES

Andrade, K., Guerra, S. & Debut, A. (2014). Fullerene-Based Symmetry in Hibiscus rosa-sinensis Pollen. *PLOS ONE* 9(7): e102123. https://doi.org/10.1371/journal.pone.0102123

Cowen, R. (2013). *History of life: Fifth edition*. Willey-Blackwell, Oxford, 302 p. https://www.wiley.com/en-us/History+of+Life%2C+5th+Edition-p-9781118510933

Grünbaum B. & Motzkin, T. S., (1963). The Number of Hexagons and the Simplicity of Geodesics on Certain Polyhedra. *Canadian Journal Mathematics*, 15, 744–751. https://www.cambridge.org/core/journals/canadian-journal-of-mathematics/article/number-of-hexagons-and-the-simplicity-of-geodesics-on-certain-polyhedra/F000206761E310E4813F76CF9011DB63

Haymet, A. D. J. (1986). Footballene: a theoretical prediction for the stable, truncated icosahedral molecule C60, *Journal of the American Chemical Society*.108:319–321. https://pubs.acs.org/doi/10.1021/ja00262a035

Halbritter H. & Auer W (2021). Stellaria holostea. In: PalDat - A palynological database. https://www.paldat.org/pub/Stellaria_holostea/306417

Katz, E. A. (2008). Fullerenes, *Carbon Nanotubes and Nanoclusters: Genealogy of Forms and Ideas* [in Russian], Moscow: Editorial URSS. https://www.bgu.ac.il/~keugene/ Publications/Popular%20paper/Katz%20fullerene%20book.pdf

Katz, E. A. & Jin, B.-Y. (2016). Fullerenes, Polyhedra and Chinese Guardian Lions. *Mathematical Intelligencer*, 38 (3) 61-68. https://doi.org/10.1007/s00283-016-9663-0

Kedves, M., Pardutz, A. & Madarasz, M. (2000). New Data on the molecular symmetry and organization of the quasi-crystalloid skeleton of the sporoderm. *Plant Cell Biology and Development*, V. 16, p. 184-192. http://acta.bibl.u-szeged.hu/47880/1/plant_cell_011_184-192.pdf

Kedves, M. (1989). Quasi-crystalloid biopolymer structures of the sporoderm and its highly organized degrees. *Acta Biol*. Szeged, 35, 59-70. http://acta.bibl.u szeged.hu/22125/1/ biologica_035_059-070.pdf

Kroto, H., Heath, J., O'Brien, S., Curl, R. & Smalley, R. (1985). C60: Buckminsterfullerene. *Nature* 318, 162–163. https://doi.org/10.1038/318162a0

Wodehouse, R. P. (1929). The Origin of Symmetry Patterns of Pollen Grains. *Bulletin of the Torrey Botanical Club*, 56(7), 339–350. https://doi.org/10.2307/2480750

Zhu, L., Zhang, T. & Teeri, Tetraketide, T.H. (2021). α-pyrone reductases in sporopollenin synthesis pathway in Gerbera hybrida: diversification of the minor function. *Hortic Res* 8, 207. https://doi.org/10.1038/s41438-021-00642

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[1] Source: Wikipedia https://commons.wikimedia.org/w/index.php?curid=14840522

[2] Source: Halbritter and Auer, 2021, PalDat - Palynological Database, public domain. https://www.paldat.org/

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