

Athens Journal of Sciences

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Gregory T. Papanikos
President
Athens Institute



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- Greek Night Entertainment (This is the official dinner of the conference)
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- Social Dinner
- Mycenae Visit
- Exploration of the Aegean Islands
- Delphi Visit

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Use of Polymer Fiber to Improve Resistance to Rutting and Stripping for HMA with RAP

By Hani Alzeraie^{*}, Ashraf Rahim[±], Shadi Saadeh[°],
Chase Plager[•] & Aaditya Ojha[°]

A great percentage of highways and roads in California are constructed with Hot Mix Asphalt (HMA) and, as California infrastructure ages, these highways and roads must be maintained and rehabilitated. Reclaimed Asphalt Pavement (RAP) is considered an excellent alternative to virgin (raw, unprocessed) materials because it reduces the use of virgin aggregate and binder. Also, the use of RAP decreases the amount of construction waste placed into landfills. This laboratory study investigated the effect of two different polymer fibers on the mechanical properties of HMA with RAP. Three different HMA with RAP mixes were used in the study. One mix that is commonly utilized on the Central Coast of California contained 15% RAP while the second and third mixes contained 25% and 40% RAP. Three different fiber dosages (0.05%, 0.10% and 0.15% of the total mix) were investigated. Specimens were prepared and tested for rutting and moisture sensitivity using Hamburg Wheel Tracker (HWT). Test results showed that adding fibers improved resistance to rutting for mixes with RAP content higher than 25%. Also, adding fibers improved mixes resistance to moisture damage. In addition, one of the two fibers used in the study outperformed the other. Overall, results indicate that adding polymer fibers to HMA mixes containing RAP has the potential to improve mixes resistance to rutting and moisture damage depending on fiber dosage and type. This study offers information valuable to the maintenance and rehabilitation of roads and highways.

Keywords: Polymer Fiber, HMA, Rutting Resistance, High RAP, Stripping

Introduction

Continuous road and highway construction is creating a scarcity on the limited source of natural aggregates. To conserve these non-renewable resources, reclaimed asphalt pavement (RAP) is being used in hot mix asphalt (HMA) at a small percentage all over the United States (Sabahfar et al., 2016). The source of RAP has more impact on the cracking performance of HMA than the quantity of RAP (Sabahfar et al., 2016). One of the methods of performance improvement of HMA is

^{*}Associate Professor, Department of Civil and Environmental Engineering, California Polytechnic State University, USA.

[±]Professor, Department of Civil and Environmental Engineering, California Polytechnic State University, USA.

[°]Professor, Department of Civil and Construction Engineering Management, California State University-Long Beach, USA.

[•]Department of Civil and Environmental Engineering, California Polytechnic State University, USA.

[°]Department of Civil and Construction Engineering Management, California State University-Long Beach, USA.

to modify the asphalt binder. Among several modification methods, fiber modification of asphalt binder has gained great attention to researchers. However, the choice of fiber type is not limited.

Corn and cotton straw fibers were used in the study of Wang et al. (2023) and the effect of fiber types on the performance of asphalt binder were investigated. Asghar and Khattak (2022) investigated the impact of different aggregate gradations on the fracture characteristics of Polyvinyl Alcohol (PVA) fiber modified HMA. Carbon Nano-fiber (CNF) modified HMA mixtures show significant improvement in terms of fatigue life and resistance to permanent performance. However, CNF modification does not affect the toughness characteristics and indirect tensile strength (Khattak et al., 2013).

Behnia et al. (2023) investigated the low temperature cracking behavior of aramid fiber (a kind of organic polymer) modified asphalt mixtures. Klinsky et al. (2018) used a mixture of polypropylene and aramid fibers to modify dense graded HMA and compared the mechanical characteristics with a control mix with no fiber. The results showed that fiber modified HMA can perform better in terms of rutting resistance and fatigue cracking resistance, but in terms of moisture resistance fiber modified HMA showed similar result to conventional HMA.

Khan et al. (2023) compared four types of fiber - carbon, fiberglass, basalt, and polyolefin/aramid (PFA) mix using two different binder grades, PG 58–28 unmodified and PG 76–22 polymer modified binder.

The research of Calabi-Floody et al. (2022) indicated polymer fibers processed from End-of-Life Tyres (ELT) can significantly improve mechanical performance of HMA.

Ceramic fiber can be another potential modifier for asphalt binder. Arabani and Shabani (2019) modified binder with 1%, 3%, and 5% of ceramic fibers content and investigated the effect of modification on both binder and mixture level. The tests concluded that ceramic fiber modification has a positive effect on high temperature rutting resistance, but negative impact on low temperature cracking resistance. The study also concluded the optimum ceramic fiber content to be 3%.

Waste paper fiber, which is a cellulose base fiber, can also be used for fiber modification. The study of Hameed et al. (2021) concluded that incorporation of waste paper fiber up to 0.7% can decrease penetration by 45% and increase softening point by 27%.

In general, regardless of the fiber type, use of fibers require higher optimum binder content as the light components of binder are absorbed by the fiber (Slebi-Acevedo et al., 2019). Again, all fibers can have a positive impact on the mechanical properties of asphalt mixtures when used at their optimum content.

Very little information is available in the literature on the effect of fiber modification along with RAP incorporation. Therefore, evaluation of fiber reinforcement in HMA that contains high percentage of RAP is recommended. Should the addition of polymer fiber proves successful in improving the performance of HMA with high RAP contents, it will help in preserving the natural resources for future generations.

Objective

The primary objective of this study is to investigate the effect of two different types of polymer fibers on the resistance to rutting and moisture damage of HMA containing various RAP percentages, specifically 15%, 25%, and 40%. The outcome of this study will help pinpoint the most effective fiber type and dosage for various RAP contents.

Methods

Materials

This study investigated three distinct HMA mixtures, each incorporating a different percentage of RAP. The first mixture contained 15% RAP utilizing a PG 64-10 asphalt binder with an optimum binder content of 5.6% by mix total weight was supplied by CalPortland. The second and third mixtures contained 25% and 40% RAP utilizing a PG 58-22 asphalt binder and were supplied by Granite Construction. As per the provided JMFs, the 25% RAP mix had an optimum binder content of 4.8%, whereas the 40% RAP mix was formulated with a slightly higher optimum binder content of 5.2%.

Detailed aggregate gradations employed in these mixes are summarized and presented in Table 1.

Table 1. Gradation of combined Aggregate Blend for the Mixtures used in the Study

Sieve Size	15% RAP (% Passing)	25% RAP (% Passing)	40% RAP (% Passing)
1 in	100	100	100
¾ in	100	98	98
½ in	97	83	82
⅜ in	83	74	73
#4	51	52	51
#8	38	33	32
#16	27	22	22
#30	18	15	16
#50	11	10	11
#100	6	6	8
#200	3.3	4.3	5.5

Two types of polymer fibers, that are commercially available were investigated. As shown in Figure 1, Fiber A was a wax-coated para-aramid fiber (maximum 37% by weight) and Fiber B was a para-aramid fiber treated with a liquid emulsion binder (maximum 25% by weight), both of which were manufactured by Surface Tech. These fibers were added to the HMA mixtures at three different dosages: 0.05%, 0.10%, and 0.15% of the total HMA weight. Control mixtures, without any fiber addition, were also prepared for each RAP content to serve as a baseline. It is noted that the 40% RAP mixture was only tested for Fiber Type-B.

Figure 1. *Fibers used for the Study: Aramid fiber Type A (left) and Type B (right)*

The naming for the samples in this study includes the RAP content, fiber type, and fiber dosage. For example, "15-A0.10" indicates a mix with 15% RAP with Fiber A, and 0.10% fiber content. Control samples are labelled with a "C", such as "25-C", representing a mix with 25% RAP and no fiber.

Specimen Preparation

For the HWT test, cylindrical specimens with a diameter of 150 mm and a thickness of $60 \text{ mm} \pm 1 \text{ mm}$ were prepared. Samples were molded to have their air void content within $7.0\% \pm 0.5\%$. The specimen preparation involved several key steps. First, all aggregates were dried to a constant weight. Then, aggregates were batched according to the JMF. The batched aggregates, including RAP, and asphalt binder were heated to the specified mixing temperature, which varied based on the PG binder grade. Heated aggregates were introduced into a mechanical mixer.

The binder and, for modified mixes, the fiber additives were then added and mixed until all particles were uniformly coated. The loose HMA mixture was subjected to short-term aging (conditioning) for two hours to simulate aging during plant production and hauling. Finally, the conditioned mixture was compacted in the Superpave gyratory compactor to the target air void level in accordance with AASHTO T 312.

Results and Discussion

The HWT test was performed on all HMA mixtures to evaluate rutting and stripping resistance and detailed numerical data and analysis for the different mixtures used in the study are presented in the subsequent sections.

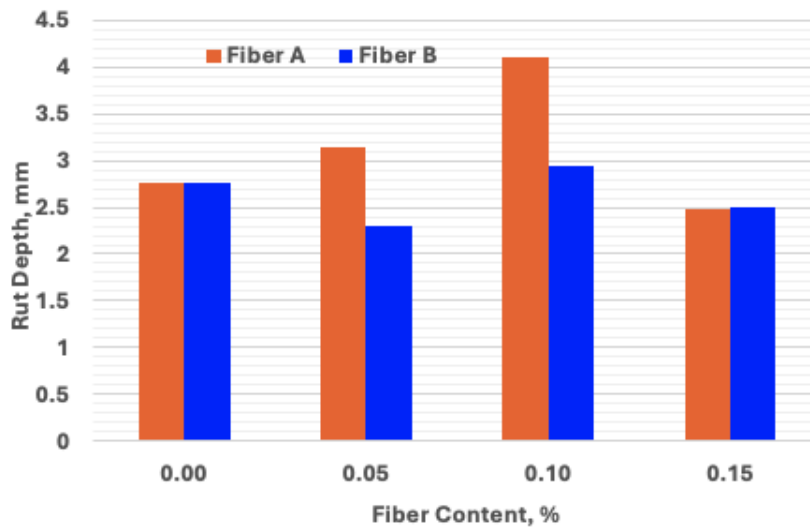
Mixtures with 15% RAP

Resistance to Rutting

Two fiber types (A and B) were added in three different percentages to HMA mix containing 15% RAP. Figure 2 presents the average rut depth measured after 15,000 passes. Fiber B at 0.05% and 0.15% slightly improved resistance to rutting compared to the control mix. Also, rut depth for mixes with fiber B performed better than mixes with fiber A at fiber percentages lower than 0.15%. However, fiber A had

a negative effect on rutting resistance for HMA with 15% RAP.

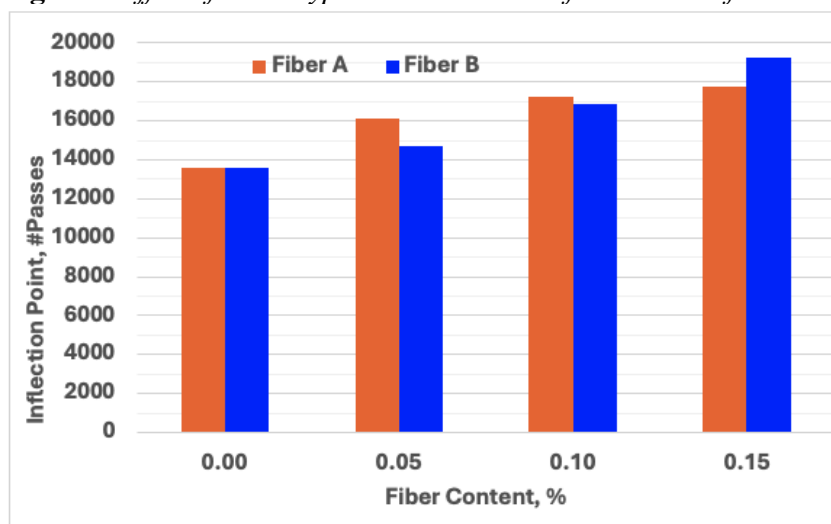
Figure 2. *Effect of Fiber Type and Content on Rut Depth for HMA with 15% RAP*



Resistance to Stripping

Inflection points can be used to evaluate stripping potential. If the stripping inflection point occurs at a low number of load cycles (e.g., less than 10,000), the HMA mixture may be susceptible to stripping. Figure 3 presents the average number of passes at inflection point for HMA mix containing 15% RAP and different fiber types and contents. Results showed that adding both types of fibers resulted in an increase in the number of passes before reaching the inflection, an indication of improved resistance to stripping. All mixes, including the control mix, resulted in number of passes higher than the 10,000-threshold.

Figure 3. *Effect of Fiber Type and Content on Inflection Point for Mixes with 15% RAP*



*HMA with 25% RAP*Resistance to Rutting

Figure 4 presents the average rut depth measured after 15,000 passes. Fiber B at 0.10% and 0.15% slightly improved resistance to rutting. However, fiber A had a negative effect of rutting resistance for HMA with 25% RAP. Also, as was observed for HMA with 15% RAP, mixes containing fiber B outperformed those containing fiber A.

Figure 4. *Effect of Fiber Type and Content on Rut Depth for HMA with 25% RAP*

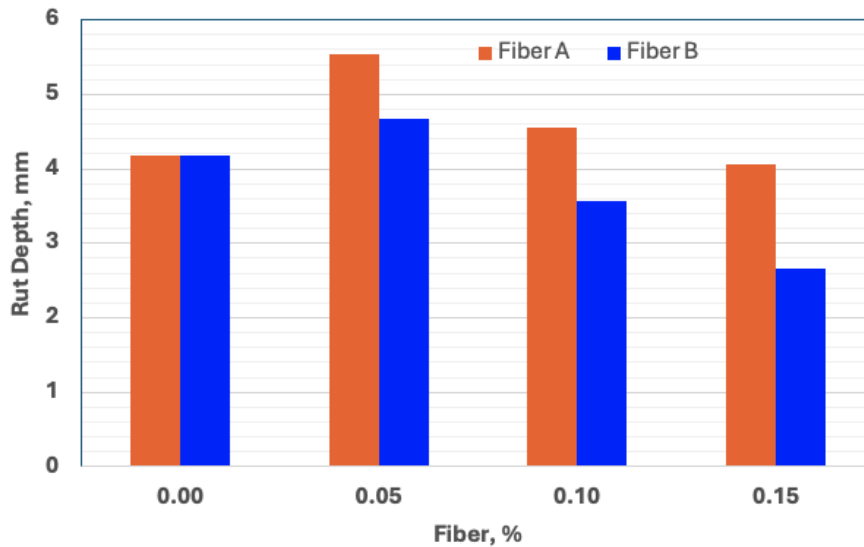
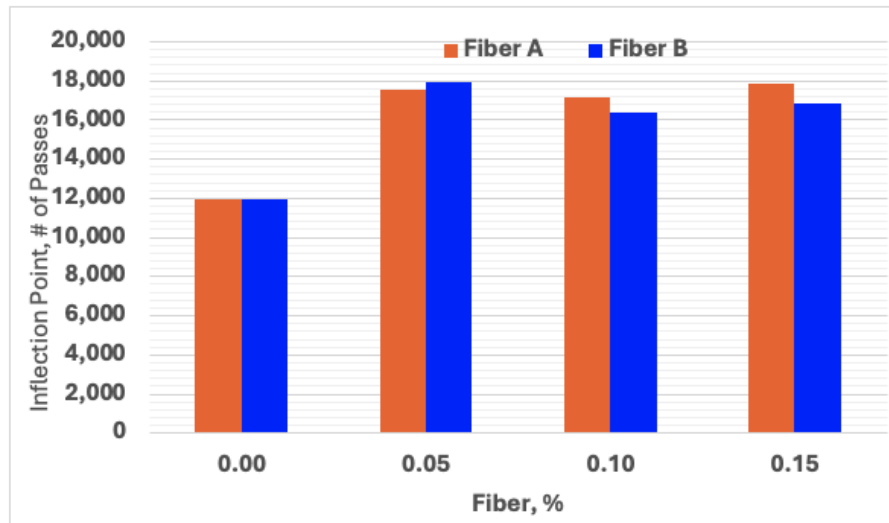
Resistance to Stripping

Figure 5 resents the average number of passes at the inflection point for HMA mix containing 25% RAP and different fiber types and contents. Results showed that adding both types of fibers resulted in an increase in the number of passes before reaching the inflection point, an indication of improved resistance to stripping. However, both fiber types performed almost equally for HMA with 25% RAP content. All mixes, including the control mix, resulted in number of passed higher than the 10,000-threshold.

Figure 5. Effect of Fiber Type and Content on Inflection Point for Mixes with 25% RAP

ANOVA Analysis

An Analysis of Variance (ANOVA) was conducted using statistical analysis software Minitab. The response variables that were investigated were limited to rut depth at 15,000 passes and number of passes at the inflection point.

Rut Depth for Fiber A vs Fiber B

To compare the performance of Fiber A versus Fiber B, the 15% and 25% RAP data were combined and sorted into two groups. Results from ANOVA analysis showed fiber B group had a lower mean rut depth at 15,000 passes than fiber A, as seen in Table 2. The difference between the means is statistically significant at the 95% confidence level (see Table 2).

Table 2. Mean Rut Depth at 15,000 Passes for the Fiber A and B Groups

Fiber Type	Mean Rut Depth at 15,000 Passes (mm)
A	3.98
B	3.10

Table 3. Differences in Mean Rut Depths at 15,000 Passes and Confidence Intervals for Fiber A and B Groups

Difference of Means (mm)	SE of Difference (mm)	<i>t</i>	Adjusted <i>p</i> -value
0.88	0.39	2.24	0.03

Inflection Point for Fiber A vs Fiber B

Fiber A had a greater mean number of passes at the inflection point than fiber B, as shown in Table 4. However, the results are not statistically significant at the 95% confidence level, as shown in Table 5. However, the results are statistically significant at a 90% confidence level.

Table 4. Mean Number of Passes at the Inflection Point for Fiber A and B Groups

Fiber Type	Mean Rut Depth at 15,000 Passes (mm)
A	16,815
B	14,788

Table 5. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for Fiber A and B Groups

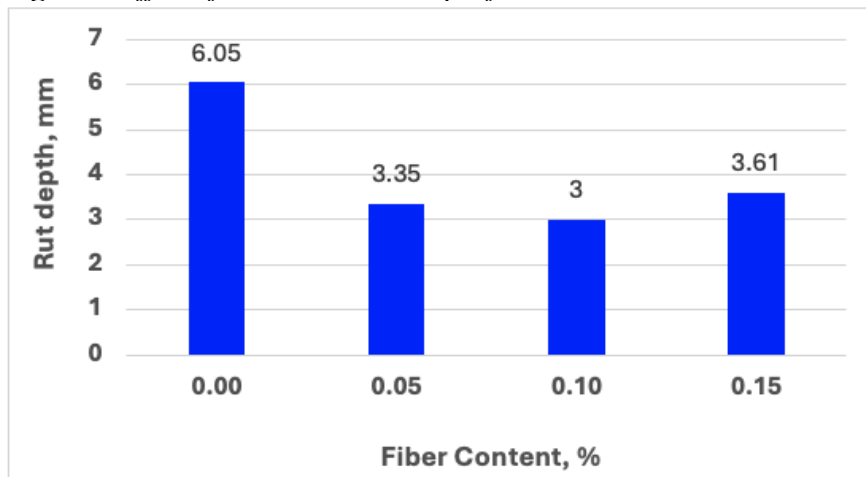
Difference of Means (mm)	SE of Difference (mm)	<i>t</i>	Adjusted <i>p</i> -value
2,027	1,274	1.59	0.10

HMA with 40% RAP

Results for mixes with 15% and 25% RAP indicated that fiber type B outperformed mixes with fiber type A. Therefore, only fiber type B was used in HMA with high RAP percentage of 40%.

Resistance to Rutting

Figure 6 presents the rut depth at 15,000 passes for HMA with 40% RAP using fiber type B added at the same dosages previously used in (i) HMA with 15% and (ii) HMA with 25% RAP. As seen in Figure fiber type B significantly improved resistance to rutting in mix that contain high RAP content. The figure also shows that fiber content of 0.1% resulted in the best resistance to rutting.

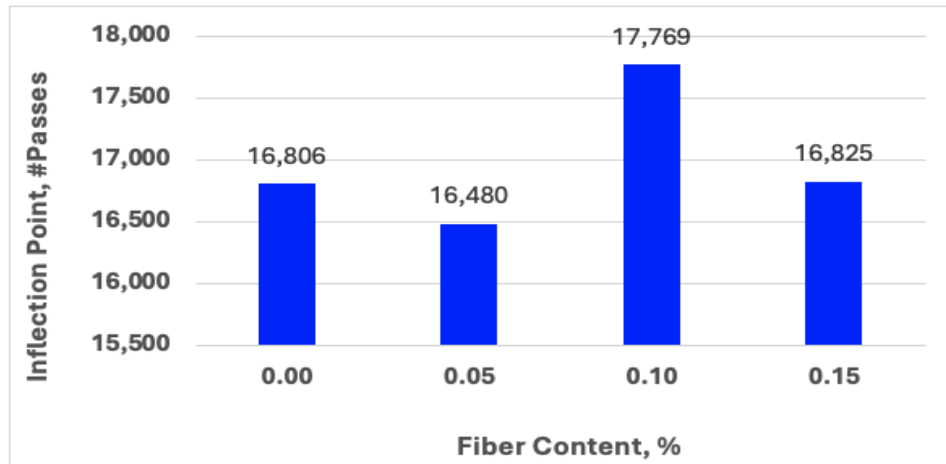
Figure 6. Effect of Fiber B on Rut Depth for Mixes with 40% RAP

Resistance to Stripping

Figure 7 presents the average number of passes at the inflection point for HMA mixes containing 40% RAP and different fiber types and contents. Results show that adding fiber B at 0.10% resulted in the highest number of passes at inflection point. However, fiber B contents of 0.05% and 0.15% resulted in approximately the same number of passes as the control mix. It is noteworthy to mention that all mixes

resulted in numbers of passes significantly higher than the 10,000 passes threshold and higher than the 15% and 25% RAP mixes.

Figure 7. Effect of Fiber B on Inflection Point for Mixes with 40% RAP



Within the 40% RAP group, there was a significant benefit to adding fiber B to the mix. Adding fiber B at 0.05%, 0.10%, and 0.15% had significantly lower mean rut depths than the control group at 15,000 passes. Table 6 shows the mean rut depths at 15,000 passes for each group, and Table 7 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 40% RAP group.

Table 6. Mean Rut Depth for the 40% RAP-Fiber B Groups

Group	Rut depth (mm) @ 15,000 passes
40% RAP Control	6.05
40% RAP with 0.05% Fiber B	3.61
40% RAP with 0.10% Fiber B	3.35
40% RAP with 0.15% Fiber B	3.00

Table 7. Differences in Mean Rut Depth and Confidence Intervals for 40% RAP-Fiber B Groups

Group Comparison	Difference in Means (mm)	SE of Difference (passes)	<i>t</i>	Adjusted <i>p</i> -value	Significance?	95% Confidence Interval
0.05% B – Control	-2.71	0.86	-3.15	0.04	Yes	(-5.26, -0.16)
0.10% B – Control	-3.05	0.86	-3.55	0.02	Yes	(-5.60, -0.50)
0.15% B – Control	-2.44	0.86	-2.84	0.05	Yes	(-5.00, -0.11)

The results were mixed for the effects of fiber on the mean number of passes at the inflection point for the 40% RAP group. The results show that 0.10% fiber B performed slightly better than the control group, while the 0.05% fiber B group performed slightly worse and the 0.15% fiber B group performed significantly worse than the control group. Therefore, there is 95% confidence that adding 0.15% fiber B to the mixture would result in a mean number of passes at the inflection point that is between 8,631 and 17,437 passes lower than the control group. Table 8 shows the mean number of passes at the inflection point for each group, and Table 9 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 40% RAP group.

Table 8. Mean Number of Passes at the Inflection Point for the 40% RAP-Fiber B Groups

Group	# of Passes at the Inflection Point
40% RAP Control	16,806
40% RAP with 0.05% Fiber B	16,479
40% RAP with 0.10% Fiber B	17,770
40% RAP with 0.15% Fiber B	3,772

Table 9. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 40% RAP-Fiber B Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	<i>t</i>	Adjusted <i>p</i> -value	Significance?	95% Confidence Interval
0.05% B – Control	-327	1,318	-0.25	0.99	No	(-4446, 3791)
0.10% B – Control	964	1,409	0.68	0.90	No	(-3439, 5366)
0.15% B – Control	-13,034	1,409	-9.25	<0.01	Yes	(-17437, 8631)

Conclusion

This study evaluated the use of two types of commercially available polymer fiber to improve the resistance of HMA that contains RAP at different percentages against rutting deformation and cracking at intermediate temperatures. Using three JMFs that were provided by two pavement construction companies, specimens were prepared for testing in the HWT. Based on the statistical and other analysis of results in this study, the following conclusions can be made:

- In general, fiber type B (treated with liquid emulsion) outperformed fiber type A (wax coated) in enhancing HMA resistance to rutting.
- For mixes with 15% RAP adding fibers (regardless of the type) did not seem to improve resistance to rutting as compared with control mix. However,

when increasing RAP content to 25% and 40%, fiber type B enhanced mixture's resistance to rutting.

- For mixes with high RAP content (40%), fiber type B significantly improved resistance to rutting and stripping. Also, fiber B at 0.1% dosage resulted in the best performance as compared to 0.05% and 0.15% dosages.
- Both types of fibers (A and B) enhanced the mixture's resistance to stripping, yielding higher numbers of passes at the stripping inflection point than the control mix.
- More laboratory investigation for mixes with RAP contents of 50% and above is recommended.
- Development of case studies to evaluate the performance of these additives in the field would further benefit asphalt pavement research.
- It is recommended to conduct a life cycle cost analysis as field performance data for these mixes become available.

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Comparing AI-Based and Traditional Digital Workflows in Urban Case Study Analysis: Senior Landscape Architecture Project

By Nadia Amoroso*, Afshin Ashari[±] & Linna Chang[°]

Generative Artificial Intelligence (AI) tools are rapidly becoming embedded within landscape architecture studios, raising important questions about authorship, accuracy, and their potential to reshape core analytical and representational workflows in the classroom setting. This study evaluates the effectiveness, limitations, and pedagogical implications of AI-based design workflows and applications within an undergraduate landscape architecture curriculum. Senior-level students at the University of Guelph completed the Urban Atlas – Community Case Studies assignment, producing figure-ground maps, analytical diagrams, and public-realm visualizations for selected urban districts. Sixteen groups participated: seven employed AI-dominant workflows incorporating platforms such as MidJourney, DALL-E, Stable Diffusion, Firefly, Runway ML, Aino, Meshy, Gemini, and ChatGPT, while nine groups relied primarily on traditional digital tools including Photoshop, Illustrator, InDesign, ArcGIS, AutoCAD, Rhino, and Blender. All final submissions were evaluated blindly by external reviewers, including principals and senior associates from landscape architecture and urban design firms, using a standardized 25-point scoring rubric. Recent AI research in the environmental design disciplines has shifted from data-driven optimization and environmental modelling toward tools capable of producing images, text, diagrams, three-dimensional forms, code, and analytical diagramming with rapid iterations. Within the studio context, this technological shift raises important questions about representation, authorship, learning outcomes, and the evolving skillsets required of contemporary landscape architects. Emerging scholarship increasingly positions AI as a creative ideation platform, providing new modes of visual experimentation, conceptual development, and rapid visualizations, provided that its use is framed within critical and ethical pedagogical structures. Students using conventional design software and workflows indicate greater control over linework, mapping accuracy, hierarchy, and labeling conventions, though it can result in longer production times and less compelling visual experimentation. Reviewer comments reflected these outcomes. AI submissions were noted for visual richness and the traditional submissions were commended for stronger analytical output. The results indicate that AI tools currently function as augmentative rather than transformative components of the design studio. Their primary strengths lie in the ideation, visualization, and stylistic exploration. The traditional digital skills remain essential for accurate, measurable, scalable, and analytically outputs. The study highlights the need for pedagogical models that integrate AI literacy while preserving foundational competencies in mapping, spatial analysis, and graphic communication.

Keywords: *visual representation, Artificial Intelligence (AI), landscape architecture, site analysis, design communication*

*Professor, The University of Guelph, Canada.

[±]Associate Professor, The University of Guelph, Canada.

[°]Graduate Student, The University of Guelph, Canada.

Introduction

Artificial Intelligence (AI) tools for visualization, mapping, and analytical representation have rapidly entered the workflow of landscape architecture design studios. Their growing presence raises questions regarding authorship, accuracy, and the broader evolution of design processes (Fernberg and Chamberlain 2023). While traditional platforms such as AutoCAD, Illustrator, Photoshop, Rhino, and ArcGIS continue to dominate industry-standard production, generative AI systems, such as MidJourney, DALL-E, Adobe Firefly, Runway ML, and ChatGPT, are increasingly being adopted in the design studio classroom. These AI tools introduce alternative modes of producing analytical and visual outputs. These technologies introduce alternative modes of producing both analytical and visual outputs, often characterized by speed, automation, and stylistic variation.

The coexistence of traditional and AI-based workflows requires educators to critically assess how these approaches compare in the production of analytical urban studies. To what extent can AI tools be integrated into the design process without compromising analytical rigor? Are final drawings generated with substantial AI assistance acceptable within professional and pedagogical standards? These questions reflect broader disciplinary concerns regarding the balance between innovation and foundational skill development.

This study examines these questions within an undergraduate landscape architecture curriculum. Senior students at the University of Guelph completed a structured assignment, *The Urban Atlas: Community Case Studies*, analyzing local and international districts through figure-ground mapping, spatial analytical diagrams, and public-realm visualizations. Sixteen groups participated; seven employed AI-dominant workflows and nine relied on traditional digital workflows. External evaluators, consisting of design principals from landscape architecture and urban design firms in Canada, blindly reviewed and scored all submissions using a standardized rubric, enabling an objective comparison of output quality and analytical performance.

Literature Review: AI in Landscape and Design Education

AI research in the environmental design disciplines has progressively shifted from data-driven optimization and environmental modelling toward tools capable of producing images, text, diagrams, three-dimensional forms, code, and analytical outputs. This transformation signals not only a technological evolution but also a broader reconfiguration of how design knowledge is generated, represented, and evaluated. Within the studio context, this technological shift raises critical questions about representation, authorship, learning outcomes, and the evolving skillsets required of contemporary landscape architects. Recent academic literature suggests that AI can function as active component of the creative process in design studios, providing new modes of visual experimentation, conceptual development, and rapid feedback—provided that its use is guided by critical and ethical awareness (Mollick and Mollick 2023). Professional commentary further describes a temporary “AI buffer zone”

surrounding landscape architecture, where the discipline's ecological complexity and relatively slower digital transformation both delay and mediate AI adoption, thereby creating space for more selective and reflective integration of these tools (Mortice 2024). Emerging scholarship extends this perspective by framing AI not merely as a technical assistant, but as a cognitive extension within design education, reshaping how students formulate prompts, interpret outputs, and iteratively refine ideas (Fernberg and Zhang 2024). Comprehensive surveys of AI-generated content in landscape architecture similarly document growing adoption in tasks such as image synthesis and diagram production, while simultaneously underscoring persistent concerns regarding accuracy, reliability, and ethical integration.

Design education scholars argue that AI's value lies in its capacity to automate complex or time-intensive tasks while strengthening the designer's creative through an expanded range of representational possibilities, particularly during early design phases (Caramiaux et al. 2025, Agkathidis 2015). Rather than replacing design thinking, AI redistributes cognitive effort, allowing students to focus more intensively on evaluation, synthesis, and decision-making (Fernberg and Zhang 2024). Within landscape architecture specifically, generative tools facilitate the rapid production of compelling visualizations, conceptual landform studies, ecological scenarios, and site narratives, assisting students in articulating ideas that might otherwise remain abstract or underdeveloped (Rekittke and Hayles 2025). At the same time, these tools also introduce students to contemporary professional workflows, as more design firms incorporate AI applications for research synthesis, visualization, and early project development. At the policy level, large-scale public investments in AI research—including recent national AI institute initiatives—signal that AI will remain a strategic priority across sectors, intensifying expectations for design programs to cultivate robust AI competencies (National Science Foundation 2025). Integrating AI knowledge into studio education therefore aligns academic training with evolving industry demands and broader technological trajectories.

A considerable body of academic literature emphasizes that generative AI should operate within hybrid workflows rather than function as a substitute for analytical and technical expertise. This position is often described as a form of hybrid intelligence, in which computational systems support visualization, pattern recognition, and data processing, while human designers retain responsibility for contextual reasoning, spatial coherence, and environmental judgment (Braidon et al. 2025). Empirical comparisons between AI-generated and human-rendered landscape visualizations reinforce this hybrid approach. Although AI tools demonstrate increasing proficiency in replicating complex geometries and planting compositions, manual refinement remains essential to ensure material fidelity, contextual sensitivity, and artistic control (Ashari and Shafaghatahi 2025). These findings suggest that AI's strengths are most effectively realized when complemented by disciplinary knowledge and critical oversight.

Landscape architecture, specially, relies heavily on spatial accuracy, site and contextual understanding, and environmental data integration, areas in which generative systems remain inconsistent and occasionally unreliable. Studies evaluating AI-assisted mapping report recurring issues such as inaccurate building

footprints, omitted hydrological features, misrepresented vegetation patterns, and inconsistent land-use mapping. These limitations were also observed by students in the present studio urban analysis case study. As a result, instructors emphasize the importance of combining AI-generated images or diagrams with standard design software under informed human supervision, such as GIS, CAD, and parametric modelling platforms, to preserve accuracy and disciplinary rigor (Maniyar et al. 2025). This pedagogical position reflects broader discussions in architecture and urban planning programs, where educators argue that AI should enhance rather than displace foundational skills such as drawing, diagramming, site analysis, and evidence-based decision-making.

Beyond issues of accuracy and workflow integration, AI-driven generative models introduce new dynamics into the creative process itself. By analyzing large datasets of existing urban spaces and landscape designs, these models can reveal hidden patterns, design logics, and aesthetic strategies that may not be immediately perceptible to human designers (Doshi and Hauser 2024). This capacity for generalized learning enables designers to explore a broader and more diverse range of possibilities, potentially stimulating students' conceptual development. When combined with user-defined constraints and preferences, AI systems can function as collaborative partners, generating design alternatives that are both innovative and contextually appropriate (Wu et al. 2021). However, the pedagogical effectiveness of such collaboration depends on structured frameworks that encourage active critique and iterative refinement, rather than passive acceptance of generated outputs (Fernberg and Zhang 2024, Braiden et al. 2025).

In addition to idea generation, AI enhances scene simulation and visualization in landscape design. Recent comparative studies evaluating AI-generated renderings against traditional human outputs using metrics such as structural similarity indices (SSIM) and cosine similarity demonstrate that AI can achieve high levels of geometric and compositional alignment, although material inconsistencies and biased outputs persist (Ashari and Shafaghati 2025). With increasingly refined modelling capabilities, students can produce three-dimensional representations of proposed sites, simulate environmental conditions, model vegetation growth patterns, and anticipate pedestrian movement (Lovett et al. 2015). These capacities contribute to the development of a visual language capable of communicating spatial, ecological, and social dynamics in more tangible and accessible ways. Moreover, AI is increasingly integrated into conventional design software such as AutoCAD, SketchUp, and Photoshop through intelligent plug-ins (e.g., Enscape Premium). These integrations allow for fast rendering of design concepts, enabling clients and stakeholders to interact with and evaluate proposals in real time, and facilitating quick design iterations. The result is a more iterative and participatory design process, enhancing the clarity and appeal of landscape proposals. This may contribute to increased student confidence in design communication, by allowing AI to help bring their visions onto paper.

In other studio development projects, when the students are required to document prompts, evaluate outputs, and revise errors, they develop stronger critical thinking skills and a more deliberate design process (Agkathidis 2015, Rekitke and Hayles 2025). Similar outcomes were observed in the present studio assignment. For the Urban Atlas Projects, AI groups documented their prompts

used, the workflow, document any errors and evaluate the AI tools they used. Students learned to critique generative tools, allowing them to judge the inaccuracy and think more about the analytical mapping, which reinforces core disciplinary values such as interpretation, iteration, and judgment. This process aligns with emerging calls for AI literacy in design education, emphasizing not only operational familiarity but also the ability to interrogate data sources, recognize algorithmic bias, and evaluate reliability (Braiden et al. 2025). Such calls for AI literacy resonate with broader work on interdisciplinary collaboration, which identifies structural and cultural barriers that must be addressed when integrating new forms of expertise into established disciplines (Institute of Medicine 2000).

Ethical considerations are increasingly embedded within pedagogical discussions of AI integration. Educators highlight concerns related to authorship, transparency, bias, and data sourcing, advocating for explicit classroom strategies such as attribution guidelines, source verification, and critical examination of the environmental and social implications of training datasets (Maniyar et al. 2025). Recent applied research in landscape visualization further emphasizes the importance of documenting AI workflows, including prompt engineering strategies, detailed reporting of checkpoints, and dataset sources, to promote transparency, reproducibility, and ethical accountability in AI-assisted design processes (Ashari and Shafaghati 2025). When implemented within such structured and reflective frameworks, AI functions not merely as a productivity enhancer, but as a medium through which students engage in informed and critical digital practice (Fernberg and Zhang 2024).

Recent literature suggests that AI's role in the landscape architecture studio is most effective when positioned as an additional layer that enhances conceptual exploration, representational diversity, and writing support for proposals, while traditional mapping, spatial analysis, and model-building continue to rely on established technical platforms and disciplinary expertise. Within this balanced configuration, AI expands the representational range and enhances new modes of inquiry appropriate for contemporary landscape challenges.

The research explores:

- (1) How AI-based workflows differ from traditional workflows in producing analytic and visual content, meaning are there challenges encountered by students that output are incorrect, e.g., figure-ground results.
- (2) Whether external reviewers can detect differences in workflow quality.
- (3) How emerging AI workflows may influence pedagogical structures and skill expectations.

Methodology

Research Design

Sixteen groups, each comprising three to four senior-level undergraduate students, were analyzed across two parallel workflow streams.

AI Workflow Groups (n = 7): Groups in this stream were required to integrate generative artificial intelligence tools throughout the majority of their design and representation tasks. Tools included MidJourney, DALL-E, Stable Diffusion, Firefly, Runway ML, Aino, and ChatGPT. Minor non-AI refinements (e.g., post-processing in Illustrator or Photoshop) were permitted to support layout precision and graphic clarity. These groups were required to submit detailed documentation of their iterative design processes, including prompt development, image generation logs, workflow diagrams, and reflective notes on technical and conceptual challenges.

Traditional Digital Workflow Groups (n = 9): These groups employed conventional digital design and mapping workflows without the use of generative AI. Production methods included Adobe Photoshop, Illustrator, and InDesign, as well as AutoCAD, Rhino, ArcGIS, and Blender, supported by literature-based and precedent-based research practices typical of landscape architecture and urban design studios.

All groups were assigned identical project briefs, timelines, and deliverables to ensure comparability across workflow conditions.

Assignment Structure

Each group was required to produce a sequence of three analytical and representational panels:

Panel 1: Figure–Ground Mapping

Mapping of built-form fabric for a 1 km × 1 km urban area within a major city (e.g., Lower Manhattan, New York City), at 1:2000 scale, including:

- Traditional building figure–ground
- Vegetation figure–ground mapping
- Street and block morphology figure–ground

Panel 2: Analytical Diagrams

Various urban analysis of the study area, including:

- Mobility and circulation networks
- Public realm typologies
- Land-use and building-use distributions
- Identification of underperforming or opportunity areas requiring design improvement

Panel 3: Public Realm Visualization and Identity of Place
Advanced representational studies including:

- Character and experiential studies of public space
- Street sections at various scales
- Quality of space and materiality visualizations

Across all panels, clarity, accuracy, visual hierarchy, and professional standards of graphic communication were emphasized.

Evaluation Framework

Sixteen final submissions were reviewed by seven external evaluators, consisting of principals and senior associates from leading landscape architecture and urban design firms. All reviewers evaluated the work anonymously using a standardized scoring rubric:

- Graphic Quality and Visual Communication (10 points)
- Site Analysis and Urban Understanding (10 points)
- Creativity and Critical Thinking (5 points)

Total possible score: 25 points

The reviewers were not informed of the workflow type used by any group, ensuring a blind peer-review structure and reducing the risk of evaluative bias. Inter-rater reliability among the seven reviewers was assessed using an intra-class correlation coefficient (ICC), calculated with a two-way mixed-effects model for average measures (ICC(3,k)), the results of which are reported in section 3.1.

Data Collection

Three primary datasets were collected:

Student Submissions

Panels constituted the core visual and analytical dataset. All submissions were anonymized and labeled only by group number (e.g., Group 1, Group 2). Projects were compiled into standardized digital PDF packages and distributed to external reviewers for scoring.

AI Workflow Documentation

Groups using AI tools submitted supplementary process documentation to the instructors, including:

- Prompt development strategies
- Tool selection rationales
- Iterative workflow diagrams

- Reflections on technical limitations, ethical concerns, and authorship perceptions

These materials served as qualitative data to support interpretation of design outcomes and student learning experiences.

External Reviewer Scores

Quantitative data were collected from scoring sheets completed by external reviewers. These data provided measurable comparisons of performance across both workflow streams.

Analysis

Quantitative Analysis

Descriptive and inferential statistical methods were used, including means, medians, standard deviations, independent-sample t-tests, and effect size calculations using Cohen's *d*, to evaluate differences between workflow groups.

Qualitative Analysis

Thematic coding has been applied to student reflections and reviewer comments to identify recurring patterns related to authorship, accuracy, efficiency, creativity, and the perceived legitimacy of AI-assisted and traditional workflows.

All groups were given three and a half weeks to complete the assignment. Groups were formed to include diverse skill sets, and participation in the AI workflow has been voluntary rather than assigned, allowing students to opt into experimental AI use. AI-based groups were required to submit full prompt logs, workflow descriptions, and reflections on challenges encountered when using these tools.

To maintain anonymity and remove presentation bias, projects were submitted without oral presentations. Some groups have used paid AI platforms such as Aino, mainly for mapping and diagrammatic tasks, while others used free or open-access tools due to financial constraints. This variation has been documented and considered as a contextual factor in interpreting workflow performance.

Methodological Limitations

Several methodological considerations should be acknowledged when interpreting the findings of this study. First, participation in the AI workflow was voluntary rather than assigned. Students who opted into this condition may have had greater prior familiarity with generative tools or stronger motivation to engage with emerging platforms, factors that could independently influence output quality regardless of the tools themselves.

Second, access to AI tools was not consistent across workflow groups. Some groups used paid platforms, particularly Aino (approximately 20 CAD per month for the student subscription) and upgraded versions of MidJourney, which provided greater mapping precision and functionality than the free-tier

alternatives available to other groups. This disparity in tool capability introduced an uncontrolled variable within the AI condition, meaning that differences in performance among AI groups may have reflected variations in resource access as much as differences in student skill or approach. An additional complication emerged during the workflow process when some groups discovered that switching between data sources within Aino, such as from Microsoft to OpenStreetMap (OSM), resulted in substantially different levels of spatial completeness. This variability was neither disclosed in advance nor controlled across groups. Future studies should standardize tool access across participants or stratify analyses by subscription level in order to more accurately isolate the influence of AI tool quality on output performance.

Results

Quantitative Scoring Outcomes

Prior to comparing workflow outcomes, inter-rater reliability was assessed to confirm the consistency of the external evaluation. The ICC(3,k) = 0.796 (95% CI for single-measure ICC(3,1): [0.174, 0.615]), $F(15, 90) = 4.905$, indicating good reliability among the seven reviewers. These results support the validity of the blind scoring procedure as a dependable basis for comparing workflow performance.

Blind reviewer scoring showed minimal difference between workflows.

Project-level means:

AI groups: 18.48 / 25

Traditional groups: 19.15 / 25

Difference: 0.67 points

Individual reviewer ratings (n=112):

AI mean: 18.85

Traditional mean: 19.48

Difference: 0.63

Effect size: $|d| \approx 0.19$ (small)

A two-sample t-test indicated no statistically significant difference ($p > .05$), confirming that workflow type did not predict higher or lower reviewer evaluation.

Table 1. Scoring from the External Evaluators – AI vs non-AI Applications

(AI Application vs Conventional Software)	Group	R1	R2	R3	R4	R5	R6	R7	Average Score
NO AI	G1	19	18	20.5	20	20	17	22.5	19.88
A	G2	20	20.5	18.5	18	18	20	21.5	19.64
A	G3	18	18.5	18	20	17	20	24	19.80
A	G4	18	21	19	17	14	18	22	18.43
A	G5	18	21	18.25	18.5	18	17	18	18.96
A	G6	22	20.5	21	22	18	22	22	21.21
NO AI	G7	18	19	19	18.8	17	21	18	18.07
NO AI	G8	24	19.5	20.5	20	21	22	23.8	21.80
NO AI	G9	23	20.5	20.75	21	14	21	24	20.81
A	G10	22	18	18.5	18	3	18	18.3	18.87
NO AI	G11	21	18	18	18	12	22	20.5	18.64
A	G12	23	19.5	20.5	19	17	21	24.5	20.64
NO AI	G13	22	20	18	21	12	22.5	24	20.21
NO AI	G14	25	21	19	19.5	12	24	18	19.79
NO AI	G15	25	21.5	18.5	20	12	21	24	20.71
NO AI	G16	21	18.5	19.2	18	4	18	18.5	18.14

Based on Table 1, the results show minimal difference between AI-assisted and non-AI workflows in overall performance, as measured by external reviewers. Average scores across both groups cluster within a narrow range (generally between approximately 18–21 out of 25), suggesting that the use of generative AI tools did not produce a statistically or perceptually significant improvement in project outcomes when compared with conventional digital production methods. Reviewers’ scores show consistent overlap across both cohorts, indicating that professional evaluators did not perceive strong distinctions in graphic quality, urban analysis, or conceptual rigour attributable to workflow type. This suggests that, within the timeframe and complexity of the assignment, AI functions more as an efficiency or exploratory aid rather than as a significant part of design excellence.

These results align with emerging scholarship in landscape architecture and design education that positions AI as an augmentative rather than transformative studio tool. Recent studies in *Landscape Journal*, *JoDLA (Journal of Digital Landscape Architecture)*, and *LA+* have reported that while generative AI can accelerate image production, expand stylistic exploration, and support rapid prototyping, it does not inherently improve spatial reasoning, site analysis, or critical design thinking. Research by Fernberg and Chamberlain (2023) has similarly noted that AI-supported visualization enhances speed and surface-level iteration, but that deeper landscape intelligence remains dependent on human interpretation, disciplinary knowledge, and iterative design judgment.

Studies examining AI in architecture and landscape studios have found that students using AI often produce visually compelling outputs more quickly. Students

using conventional GIS, CAD, and modeling workflows tend to demonstrate stronger control over scale, measurement, and spatial legibility. These findings reinforce the results of this study: reviewers did not observe strong qualitative differences between AI and non-AI groups because visual richness alone did not outweigh the importance of analytical rigour and spatial clarity.

Reviewer Feedback

AI submissions are applauded for visually sophisticated perspectives, atmospheric images, and stylistic branding. However, reviewers have also noted occasional issues with hierarchy, analytical integrity, and consistency.

Traditional submissions have shown strong control of mapping accuracy, labeling, and structured layout, though some have received comments noting less dynamic imagery or lower creativity.

Student-Reported Workflow Insights

A review of the submitted AI workflow documentation revealed that figure-ground inaccuracies were a recurring issue across most AI groups. Of the seven AI workflow groups, five documented the need for manual correction of AI-generated base maps, citing missing building footprints, incomplete street geometries, absent vegetation layers, and misclassified land-use boundaries. In all cases, these corrections were completed after generation using Illustrator or Photoshop, demonstrating that even AI-dominant workflows ultimately depended on hybrid production methods to achieve professional cartographic standards.

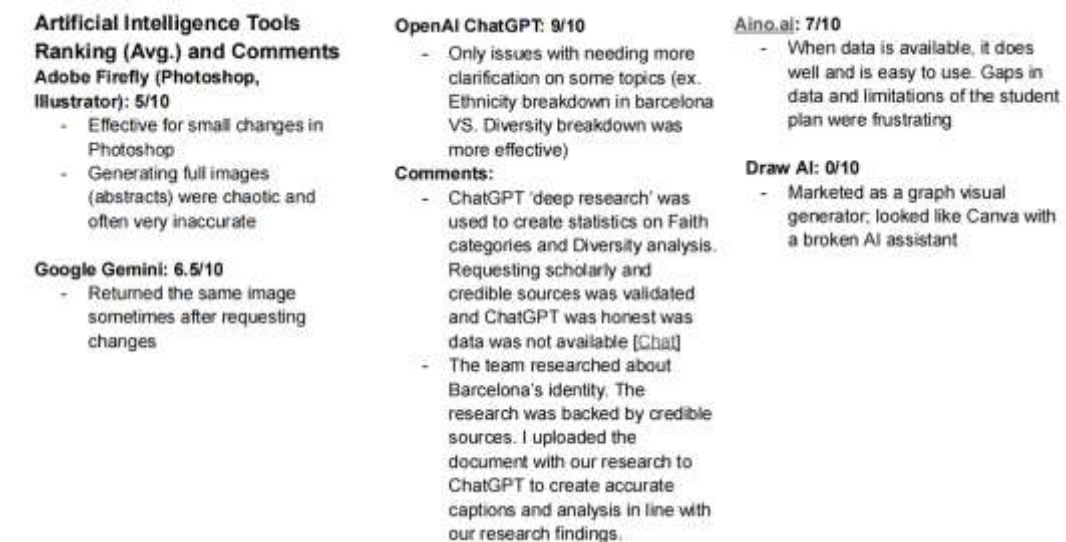
The workflow documentation submitted by Isabella Stasiulis, Habiba El Shamy, and Matteo de Florentiis provides detailed evidence of these challenges. Using Aino as the primary mapping platform, the team identified data insufficiencies across multiple analytical layers. Tree and green space data were incomplete and required manual additions. Building block courtyard infill was absent from the AI outputs and later corrected in Photoshop. Land-use typology mapping was partially misclassified because of gaps in the source data, while thin pedestrian paths were missing from the street network layer and subsequently added manually in Photoshop. The team further noted that AI tools were unsuitable for producing scale-accurate massing models or technical sections, leading them to rely on CADmapper and manual Photoshop workflows for precision drawing tasks. As noted in their reflective documentation, “AI is NOT effective at generating accurate, to-scale sections of real-world built form.”

Similar challenges were documented by Natasha Rees, Emily Pham, and Krish Jain in their analysis of the Eixample and Gothic Quarter districts of Barcelona. An initial figure-ground prompt using Aino’s Microsoft data layer produced incomplete outputs, with partial or entire buildings missing. The students identified this issue not as a prompting failure, but as a limitation of the underlying data library, including the incompleteness of OpenStreetMap datasets. Street network layers introduced additional problems, as pedestrian highways were incorrectly rendered as filled black areas. Multiple rounds of prompting failed to resolve the issue, ultimately requiring manual correction in

Gemini and Photoshop. Vegetation data also failed to align with satellite imagery. Circulation mapping required supplementary datasets from Barcelona’s Open Data portal, while pedestrian sidewalks were cross-referenced against Google Earth and manually added in Illustrator. These examples suggest that AI-assisted mapping currently functions more reliably as a preliminary analytical tool requiring subsequent human verification and refinement, rather than as a finished analytical product.

AI teams also reported significant efficiency gains in perspective rendering, texture generation, and stylistic experimentation. However, these advantages were consistently offset by limitations in scale-dependent drawing tasks. Prompt iteration consumed substantial amounts of time, and final panel composition still required manual assembly in Illustrator or InDesign because generative tools were unable to manage layout, labeling, and spatial hierarchy at a professional standard.

Figure 1. AI Tool Performance Ratings Submitted by a Representative AI Workflow Group



Students: Natasha Rees, Emily Pham, Krish Jain.

The end-of-project evaluation of individual AI tools (see Figure 1) further reflects this uneven performance across task types. ChatGPT received the highest rating among the tools used (9/10), primarily because of its effectiveness in generating written analysis, synthesizing research findings, and producing contextually accurate captions for graphic panels. Aino received a rating of 7/10. While it performed adequately when source data was available, its effectiveness was constrained by data gaps, limited prompt and export quotas under the student subscription plan, and an underdeveloped editing interface. Google Gemini received a rating of 6.5/10, with students reporting recurring difficulties in prompt interpretation, particularly when attempting targeted edits to previously generated images. These issues frequently required restarting chat sessions to reset the workflow. Adobe Firefly, including Photoshop and Illustrator integrations, received a rating of 5/10, with usefulness largely restricted to minor localized edits rather than full-scale image or map generation. EDraw AI received a rating of 0/10

because its functionality was considered inadequate for the analytical demands of landscape architecture workflows.

Traditional workflow groups reported longer production times but consistently fewer issues related to accuracy, spatial control, and output consistency. Unlike the AI groups, they reported little need for post-processing correction of base maps or analytical layers.

Summary of Workflow Traits

AI workflows:

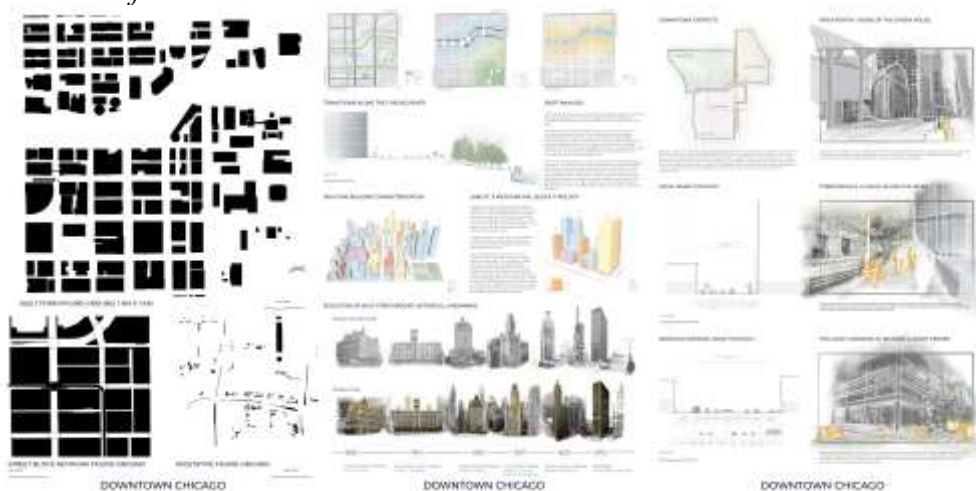
- High visual appeal; rapid iteration
- Lower reliability in scale accuracy
- Requires hybrid post-processing

Traditional workflows:

- High control, accuracy, consistency
- Slower production
- Less experimental image generation

Across the submissions, recognizable patterns have emerged at the panel level rather than in the overall reviewer scores. Conventional panels, such as Figure 2, which represents a typical project submission, demonstrate strong figure-ground reliability, precise line-work, and controlled image placements in the panel layouts using Illustrator, InDesign and Photoshop-based production. Students using traditional workflows generally have exhibited more consistent cartographic accuracy, correct labeling conventions, and well-structured layouts and visual hierarchies.

Figure 2. *Example of Panel Submission from Students Using Non-AI Applications and Workflow*



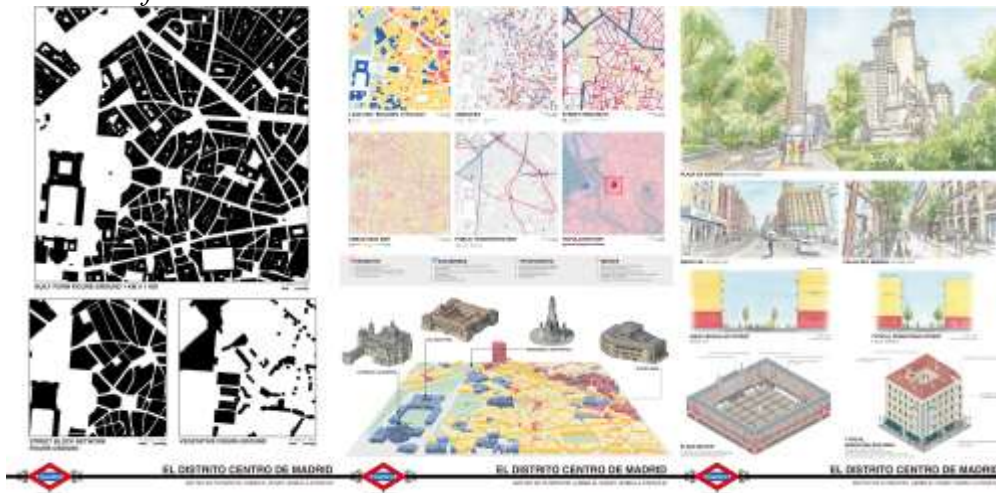
Students: Sarah Letourneau, Joyce Carrera, Sara Stekar.

In regards to the AI-led panels, these typically have showcased rapid, visually appealing outputs with strong atmospheric qualities and stylized renderings. The base maps generated through AI workflows frequently have required correction in Illustrator or Photoshop to fix imperfect building footprints, missing vegetative features, or misaligned street geometries. In regards to layout composition in AI panels, this has tended to be less consistent, suggesting that while generative models are highly effective at producing compelling individual perspectives, AI applications still struggle with the correct image placements on panels with the appropriate labelling. For more accurate mapping and figure-ground maps, students have often used ‘upgraded’ AI-applications such as Aino.

Across 16 projects and 112 blind reviewer scores, overall performance between AI-based and conventional workflows was essentially even. On a per-project basis, mean scores have differed by only 0.10 points on a 25-point rubric (AI = 18.48; conventional = 19.15; $n = 7$ vs. 9), a difference too small to be pedagogically meaningful. When scores are examined across all individual reviewer ratings, the gap has remained modest (AI = 18.85 vs. conventional = 19.48), with a mean difference of 0.63. A calculated effect size ($|d| \approx 0.19$) indicated a very small practical effect, confirming that the choice of workflow did not significantly influence scoring outcomes.

The reviewers’ comments further illuminate these trends. AI-generated submissions are often applauded for their “eye-catching,” visually polished images, particularly in perspective renderings and architectural character studies. See Figure 3 representing an AI panel submission. However, reviewers have also noted tendencies toward more superficial analysis, inconsistent hierarchy, or incorrect labeling in several AI-dominant panels. With the traditional workflow submissions, these are commended for clarity, accurate labeling, and analytical thoroughness, however some are critiqued for less dynamic imagery or comparatively conservative visual presentation. Collectively, these comments support the emerging research suggesting that while generative AI excels at producing compelling conceptual or early-stage visuals, it still requires human enhancement to ensure accuracy, coherence, and interpretive clarity (Li and Amoroso 2023, Liu 2024, Schroth and Maier 2025).

Figure 3. Example of Panel Submission from Students Using AI Applications and Workflow



Students: Matteo de Florentiis, Habiba el Shamy, Isabella Stasiulis.

Discussion

The student AI workflow processes highlight insight into where reviewers have perceived strengths and weaknesses in the AI-generated submissions. Perspectives and stylistic renders, such as “watercolour/sketch” effects, are produced quickly and with a more compelling visual appeal. These are used with platforms like Gemini and MidJourney. These tools have excelled in generating atmospheric images, conceptual perspectives, and mood-driven representations that would often need more time using conventional digital illustration techniques.

The students’ reflections on AI workflow processes also reveal recurring challenges. Figure-ground mapping, land-use diagrams, and vegetation layers have often required substantial manual correction due to missing features, misclassified elements, or incomplete spatial coverage produced by AI tools such as Aino. However, Aino seems to produce more accurate outcomes because of their upgraded package. In several cases, students have noted that pedestrian linkages, courtyard infill, and fine-grain urban details are omitted or inaccurately rendered, which then required their additional editing in Illustrator or Photoshop to achieve cartographic accuracy.

Although Aino demonstrates relative strength in producing initial figure-ground and mapping visualizations, its outputs still lack the precision and consistency expected in technical analysis panels. Students have reported that while AI could generate compelling starting points, these draft layers required verification and refinement against authoritative sources such as municipal open data, GIS databases, or Google Earth imagery.

AI-assisted text generation, such as SWOT analyses produced through ChatGPT, is reported as helpful for early conceptual thinking and framing the overview of selected districts. However, graphics that showcase history timeline, panel layout organization, and scale-accurate sections, have continued to rely on traditional software with manual creation. Students consistently

found that generative AI lacked the ability to maintain scale, adhere to measurement constraints, or respect conventional drawing standards, especially in analytically complex aspects.

Some of the students' comments included the following for AI usages. The platform used for mapping and diagramming work was Aino. Other AI image generators have lacked the ability to analyze the specific contextual data of the site, as they did not have access to detailed map information. As a result, the free platforms could not distinguish between different building types, complex street networks, trail systems, and waterways unless the colours of each feature have been manually adjusted to make them clearly distinguishable.

Aino itself is also limited in the data it could provide through the basic subscription. Data such as land-use zoning and specific tree diameter data are unavailable and have to be obtained separately from the official City's Open Data website. Aino does not offer the option to convert line styles to dashed lines, although it has provided three fill-pattern options for shapes. The platform also carries a cost of more than \$20 per month for the basic student version.

Even though this platform has these limitations, Aino is effective in several key areas. It is fairly successful for mapping by allowing the groups to retrieve data within a defined site radius through text prompts or by importing datasets from the City's Open Data website. The platform has enabled clear manipulation of line weights and colours for both lines and shapes, and it offers a variety of base map layers, with the option to switch to a solid background colour when preferred. One of Aino's strengths includes its ability to generate walking-radius diagrams. For instance, prompting the system to "create a 500 m radius around this pin" has produced an accurate circular buffer around the selected location, demonstrating its usefulness in basic spatial analysis and visualization tasks.

Other groups provided more feedback regarding the use and efficiency in producing maps, diagrams, and images for landscape architecture. Many groups have commented that Google Gemini performed well in crafting realistic 3D model renderings. It has frequently struggled to interpret prompts accurately, particularly when asked to edit its own generated images. As more iterations were produced, the system became increasingly inconsistent, often requiring new chat sessions to reset the workflow.

ChatGPT has been effective for generating written content, such as inventory descriptions, site analyses, and explanatory text that supports design thinking. It has not been as successful in rendering detailed or visually refined images, making it better suited for conceptual development and not customized renderings.

Meshy AI has demonstrated strong performance in creating accurate 3D models of buildings from photographs and producing meshes that could be further edited in Blender, making it useful for integration into more advanced modeling workflows. The platform requires payment to access full rendering capabilities and performs best only with individual objects, buildings, or people. It lacks efficiency when applied to large-scale neighbourhood or district-level modeling.

Aino is strong in generating visually pleasing graphic map styles, offering a variety of templates and a large selection of symbols for diagramming. The platform occasionally misinterprets or mislabels source data when generating

map content, limiting accuracy. Its interface lacks advanced editing features, including control over object shapes, colour palettes, and basic undo/redo functions.

Another group has evaluated the AI tools as the following. Adobe Firefly, used through Photoshop and Illustrator, has received an average ranking of 5 out of 10. It has been effective for making small, localized edits within Photoshop. The outputs have often been chaotic, lacking accuracy in form and overall intent. For tasks that have required precise landscape features, coherent spatial patterns, or stylized diagrammatic aesthetics, Adobe Firefly's generative capabilities are not as strong. Its usefulness has been limited to minor adjustments rather than full-scale image creation or map-based visualization.

According to the student users, Google Gemini has ranked better at 6.5 out of 10. When the group prompted the platform to revise or adjust an image, Gemini often returned the exact same output and did not applying the requested changes. ChatGPT has received a high user evaluation at 9 out of 10 due to its performance in generating written content, conducting research-supported analysis, and assisting in the creation of captions and narrative descriptions for graphic panels. In this evaluation, ChatGPT was used to perform "deep research" on topics such as demographics, cultural diversity, and urban identity, for example, for Barcelona as the case study for the urban analysis project. The platform has acknowledged when data was unavailable and has validated scholarly sources when requested. The research team uploaded their findings directly into ChatGPT, and the system successfully synthesized the material into clear, concise captions aligned with landscape architecture communication standards. For example, when prompted to write captions for the Street Network sections of Barcelona, specifically Las Ramblas and the Superblocks, the platform has generated detailed and contextually rich narrative descriptions.

According to the student users, Aino received user evaluation of 7 out of 10. When data inputs are available, the platform has performed well and has offered a user-friendly interface. It has generated visually appealing maps and diagrams and has supported a range of presentation-ready graphic styles. The platform has data missing and labeling errors, and the limitations of the student subscription plan have created barriers. Restricted access to the number of prompts, limited export options, and the absence of advanced editing tools have made the workflow not efficient.

According to the student users, EDraw AI was evaluated as a 0 out of 10, because it has functioned more like a simplified version of Canva with an unreliable AI assistant. Its outputs have lacked intelligence, accuracy, and meaningful integration with landscape architecture workflows. As a result, it has provided little practical value.

Several teams have attempted to use AI for 3D massing or spatial modeling but have found the outputs to be unreliable, inconsistent in scale, or visually distorted. Most students have reverted to hybrid workflows involving Google Earth for reference geometry, Procreate for massing sketches, or Adobe tools for refined digital models. These observations reinforce findings in recent literature emphasizing that generative AI currently struggles with geometric accuracy, reproducibility, and spatial reasoning and the limitations that require human oversight and post-processing correction.

The interpretation of the results suggests that AI-dominant workflows and traditional digital workflows currently perform at comparable levels when evaluated on professional criteria. The lack of significant scoring differences aligns with recent literature showing that generative AI excels at early-stage visualization but still depends on human oversight for accuracy and analytic depth (Li and Amoroso 2023, Liu 2024, Schroth and Maier 2025). The small effect size further supports that workflow choice alone does not determine quality.

The reviewers' comments indicate that AI advantages focus on the visual experimentation and atmospheric rendering, which are aspects that are attractive in early design phases. The analytic clarity, map accuracy, and hierarchy remain more evident in traditional workflows, supporting the importance of keeping technical proficiency in GIS, CAD, and Adobe software.

AI prompt logs revealed that students often relied on manual corrections after AI output, supporting arguments that workflow should be hybrid. AI tools demonstrated particular strengths in ideation and visual exploration, while traditional tools remained superior for precision, scalability, and analytical accuracy. AI applications are quickly evolving and this could change.

The student workflow documentation and reviewer feedback together point to a consistent pattern: AI tools contributed most effectively to visual quality and early-stage exploration, while precision, analytical depth, and cartographic accuracy continued to depend on conventional platforms and human judgment. This distinction has important implications for how AI should be positioned within landscape architecture curricula.

At present, the findings support an augmentative rather than transformative role for AI in studio education. An augmentative approach treats AI as an additional layer within an existing technical foundation, where students first develop core competencies in GIS, CAD, and graphic communication, and then use AI tools selectively to support visualization or conceptual development. A transformative approach, by contrast, would reorganize the curriculum around AI literacy as a primary learning outcome, potentially reducing emphasis on foundational technical skills. Given that the AI workflow groups in this study consistently required manual correction to address spatial inaccuracies and analytical gaps, such a transformative shift appears premature and may weaken competencies that remain essential to professional practice.

Several practical directions emerge from these findings. Maintaining GIS, CAD, and graphic communication as core studio requirements remains important. Structured AI components, in which students document prompts, critically evaluate outputs, and verify results against authoritative data sources, can be integrated alongside existing workflows rather than replacing them. Project briefs that explicitly require comparisons between AI-generated and manually produced outputs provide one practical model for implementation. Incorporating AI ethics, attribution, and source transparency as assessed elements within studio practice could further encourage informed and critical use of these technologies. As AI platforms continue to evolve, the appropriate scope of their role within design education will require ongoing reassessment.

Conclusion

The results demonstrate an overall equilibrium between traditional and AI workflows: neither approach has dominated the reviewers' scoring. The class itself has been nearly evenly divided between students using conventional software versus those more keen to explore AI-generated applications and methods. Although individual groups have been assigned a single workflow rather than testing both, each three- to four -person group has been formed to ensure balanced skillsets, and to minimize bias in comparing outputs. Several limitations include paid and free AI applications that tend to offer different benefits. Some groups did not use upgraded –paid AI applications, which could have offered more visual accuracy and customization. Other limitations include allowing both sets of groups to re-do the same project using both AI and conventional digital software. Additionally, participation in AI-based workflows was voluntary; students were not compelled to use AI applications, and only those interested in experimenting with these tools elected to do so. This self-selection may have influenced levels of engagement and outcome quality.

Overall, the findings suggest that AI tools in landscape architecture studios currently function most effectively as complementary instruments rather than replacements for traditional methods. As AI tools continue to evolve, future research should examine longer-term learning impacts, hybrid workflow models, and the potential for AI to meaningfully support ecological modelling, climate-responsive design, and evidence-based spatial decision-making, extending beyond compelling conceptual representational outputs.

The implications for pedagogy are evident, that is, students benefit most from hybrid knowledge and skills (Mollick and Mollick 2023). Generative AI offers speed, stylistic outcomes, and iterative capacity, while traditional tools remain essential for accuracy, mapping, scale, and deeper analysis. As AI platforms advance, transparency, prompt documentation, human quality control, and ethical awareness must remain central components of curriculum design. AI transforms landscape architecture by enhancing creative complexities, enhancing visualization, enabling intelligent site management, and optimizing design solutions. By integrating AI into the design workflow with more conventional design processes, landscape architectural students can improve ideation, enhance design quality, and make more evidence-based decisions.

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Explainable AI in View of Ancient Philosophy How Homer and Aristotle Perceived Artificial Intelligence

By Thomas Fehlmann* & Eberhard Kranich[‡]

Recursion is a difficult mathematical concept. It can lead to infinite loops in computers but on the other hand, if controlled, helps to train our natural neuronal network in our brain. Nevertheless, in the domain of τέχνη, recursion is difficult to handle. For Ancient Greek philosophers, such as Socrates, Plato, and Aristotle, τέχνη was a difficult term, most probably because they did not yet have the notion of mathematical recursion. The difference between γνώση resp. επιστήμη and τέχνη – observational knowledge (Gnosis) respectively science (Episteme), and technology (Techne) is reflected in today's discussion about explainable AI. This paper attempts to address today's problems with AI, whether AI becomes trustworthy, or authorities even can certify AI for safety purposes, by recurring to these antique philosophical notions. Combinatory Logic is explained, the graph model introduced, recursiveness discussed, and outlined how to make current AI explainable by defining Controlling Combinators.

Keywords: Explainable AI, Theoretical Computer Science, Graph Model of Combinatory Logic, Safe AI, Automated Decision Making, Controlling Combinators, Intelligent Systems.

Introduction

Since almost 3'000 years, robots are associated with female androids, because Homer in his Iliad, book 18, describes “golden handmaids” that “worked for him (Hephaistos), and were like real young women, with sense and reason (Nous, νόος), also voice, and strength, and all the learning of the immortals” (Homer, 2017, p. 18/419). The dream of artificial intelligence (AI) is quite old, so old, that it might be a condition for humanity. Today, that dream seems to have come true; however, its foundations are not so clear.

The Graph Model of Combinatory Logic models knowledge. It is an algebra that describes neural networks, *Natural Neural Networks* (NNN) and *Artificial Neural Networks* (ANN) alike. NNNs are a key element of nature, all living beings use some sort of neural network for survival. Humans have excelled in its use, not for survival only but for explaining physics and creating mathematics and logic, and even inventing gods that in turn create intelligent machines.

However, it is apparent that not all NNN are alike. There exist huge differences. This paper explores some of these differences to explain the prospects of current AI.

*Senior Researcher, Euro Project Office AG, Switzerland.

[‡]Senior Researcher, Euro Project Office AG, Switzerland.

Literature Review and Motivation

Obviously, there are major systemic differences between NNN and ANN. While NNN have a very dynamic way of establishing and destroying connections between neuronal nodes that is not yet well understood by neuroscientists, the invention of transformers based on attention heads that establishes these connections is relatively new in ANNs (Vaswani, et al., 2017). NNNs contain physically unrestricted loops. By contrast, loop formation in ANNs has revealed major difficulties (Barceló, Pérez, & Marinković, 2019), since Turing-completeness means that loop formation could spiral out of control, as the halting problem is undecidable for Turing machines (Turing, 1937). The formation of loops is a key feature of all types of neural networks. In more precise mathematical terms, this is referred to as recursion.

The key to intelligence in its various forms is recursion. The ability to reflect effects of our actions distinguishes brains of higher animals and humans from more primitive neural networks, for instance in insects. Some insects keep trying to fly through solid glass windows despite continuous failures. Engeler (Engeler, Neural algebra on "how does the brain think?", 2019) calls that a *Controlling Combinator* what helps brains to reflect and learn.

Homer's short statement about the handmaids of Hephaistos reflects a continuous discussion between the notions related to *Techne* (τέχνη) and to reasoning. *Techne* by itself has no way of learning, much less of learning the wisdom of the immortals (νόος). Humans sometimes learned about the intentions of the gods, preferably by help of dreams, augurs, and priests. Homer, as a founder of some sort of religion, relates many ways how to learn from the gods. In the *Iliad*, Agamemnon's dream in book two was the key to telling the Greeks what Zeus wanted from them (Homer, 2017, p. 2/7). The dream raised false expectations, and Agamemnon was unable to discern the true intention of the gods; hence, he misunderstood the dream as divine advice to successfully fight the Trojans and conquer their citadel.

If not by dreams, leaders in antiquity often used the services of augurs, birdwatchers, or with the Latin word *augurs*, to learn from bird's flights the intention of the gods, or they went to an oracle, to a *Pythia* (πυθία, the high priestess of the Temple of Apollo at Delphi, serving as oracle). Compare with the comprehensive study of the knowledge and perception of the bird's world in ancient times by Lunczer (Lunczer, 2009).

What is the relationship between oracles and birdwatching on the one hand, and *Artificial Intelligence* (AI) on the other? Both can be explained by some kind of relationship between observations and resulting effect. In the first case it is learned by tradition, in the second by a specific "training set." Aristotle would both approaches call *Gnosis* (γνώση) (Aristoteles, 367-344 BCE).

Moreover, our ability to reflect recursively does not end with such relationships. There are relationships that have no apparent cause and effect, such as the incidental coincidence between the arrival of storks and the accumulation of children's births in rural societies. Both happen in spring. Children are born because the parents have been well fed back in the previous fall's harvest, and storks return because the spring's milder climate provides enough prey, but storks bring nothing. Our neural network recognizes such relationships. Humans describe such insights as "gut feeling" that often are better than any other formal, rational approach that bothers for cause and effect (Gigerenzer, 2007).



Predictions done with generative AI use the same mechanisms as the prophecies of the Pythia (πυθία) and the dreams received by some god. In both modern and ancient terms, these are hallucinations. The difficulty with hallucinations is that it is hard to assess whether they reflect reality properly. Not only a few of our ancient augurs and πυθία effectively relied on their gut feeling when talking to their sponsors; often, their hallucinations proved valuable and right. Today's generative AI quite often produces valuable responses to questions without doing anything else than producing hallucinations. ANNs are using Gnosis (γνώση), neither Episteme (επιστήμη) nor Techne (τέχνη).

This paper explores this coincidence to explain what an AI does, and what an AI cannot provide. The *Graph Model of Combinatory Logic* (Engeler, Algebras and Combinators, 1981) explains the Gnosis (γνώση) approach, but also how an AI probably could go beyond statistical observations and start reasoning about causes and effects. This was called Episteme (επιστήμη). Finally, an approach combining Gnosis (γνώση) with Techne (τέχνη) is presented, creating intelligent systems that follow "the learning of the immortals."

Methodology and Methods

The constituting elements of the graph model are *Combinators*, defined as sets of arrow terms of the form (1):

$$x_j \rightarrow y \tag{1}$$

The nodes of origin in the graph x_j are a selection of *Observations*, selected by the choice function j , and the y represent the target node, the node receiving a stimulus from the x_j , also interpreted as observed effect. Proper arrow terms are called *Concepts*. The claim is that these combinators, consisting of observations and concepts, represent knowledge (Fehlmann & Kranich, A General Model for Representing Knowledge - Intelligent Systems Using Concepts, 2024). This definition is highly recursive because you can observe concepts. Thus, arrow terms can contain other arrow terms including concepts. This model relies on Gnosis (γνώση), neither on επιστήμη nor τέχνη.

If this powerset is based on the null set, weights in nodes play no role in equation (1). If the powerset is based on some non-empty set of observations referring to some real-world items, or some imaginary items, then weights can describe the nodes' importance with respect to the target node. This powerset describes the behavior of both artificial and natural neural networks (Engeler, Neural algebra on "how does the brain think?", 2019). The choice function j is not restricted to any "real" object observed, but to anything that impresses our neural network. A picture displaying a stork carrying a baby can as easily been selected as any modern deep fake AI-generated picture. This is the mechanism that augurs, dictators, and all kinds of populist parties use to gather their followers. In contrast, the era of enlightenment called for rational reasoning, something that neither an NNN nor an ANN provide for free. The era of enlightenment is long gone in history (Bristow, Fall 2023 Edition) but was already anticipated by Aristotle in his Organon (Aristoteles, 367-344 BCE). This is *Techne* (τέχνη). On the other hand, Plato's allegory of the cave reflects *Gnosis* (γνώση). It is not surprising that Engeler used the graph model also to investigate why Aristotle did not invent mathematical relations (Engeler, Aristotle' Relations: An Interpretation in Combinatory Logic, 2020).

Knowledge of all kinds is combined as follows. Let M and N be any combinators, then you can apply M to N :

$$M \bullet N = \{b | \exists a_i \rightarrow b \in M; a_i \in N\} \quad (2)$$

Equation (2) makes the graph model an algebra (Engeler, Algebras and Combinators, 1981). The algebra is Turing-complete because it is possible to define *Lambda Terms* that introduce a variable x in M , allowing for an application of M to some argument N (Barendregt & Barendsen, 2000):

$$\lambda x. M \bullet N \quad (3)$$

In case of equation (3), N replaces all occurrences of x in M . For formal definitions, consult (Fehlmann, Autonomous Real-time Testing – Testing Artificial Intelligence and Other Complex Systems, 2020, p. 5). In the graph model, Lambda terms contain no specific observations. It has the form of a complicated structural element whose application does not depend on its nodes' weights (Fehlmann, Managing Complexity – Uncover the Mysteries with Six Sigma Transfer Functions, 2016, p. 326ff). It is called *Lambda Concept*. For a proof of Barendregt's theorem for the graph model, see Fehlmann (Fehlmann, Theorie und Anwendung der Kombinatorischen Logik, 1981). Since Lambda concepts add programming capabilities to the graph model, it refers to *Techne* (τέχνη).

The graph model is versatile. It is possible to define models for explaining how the brain works (Engeler, Neural algebra on "how does the brain think?", 2019), give an algebraic description of *Quality Function Deployment* (QFD), see (Fehlmann, QFD as Algebra of Combinators, 2001) and (Fehlmann & Kranich, How to Explain Artificial Intelligence to Humans - Learning from Quality Function Deployment, 2024), describe software and systems testing (Fehlmann & Kranich, Testing Artificial

Intelligence by Customers' Needs, 2019), and requirements engineering (Fehlmann & Kranich, Requirements Engineering for Cyber-Physical Products, 2023). The latter works because the model includes both algorithms and cause-effect statements. Thus, it can be used for specifying requirements for intelligent systems that sometimes must adapt to the environment, based on γνώση, and sometimes implement strict rules, thus Techne (τέχνη), for instance when legal compliance, or safety, is a strict requirement (Fehlmann & Kranich, Requirements Engineering for Cyber-Physical Products, 2023). While generative AI can generate any idea, reasonable or not, lambda concepts can be used to ensure predictable behavior (Techne, τέχνη) from an *Intelligent System* (ISY)¹.

ISYs are a mix of lambda concepts and generative AI, of Techne (τέχνη) and Gnosis (γνώση). Thus, they behave partly like an ordinary program, executing rules, and partly they interpret their environment by observations made through the data received.

Cause and Effect

Although arrow terms concepts often look like they are connecting cause and effect, they do not. They connect a selected set of observations with a specific effect. Concepts might as well describe storks bringing babies as weather conditions causing storks to fly. Humans, animals, and machines learn by connecting observations with effects, not by analyzing cause and effects. This is why antique augurs and πῦθια often produced valuable prophecies. If there is a statistically significant relationship between selected observations x_j and some observable effect y , there is often a cause-effect relationship behind it, although the exact relationship remains unknown. Many sciences rely on such concepts; for instance, medicine. You accept a new drug after some tests show a statistically relevant effect, without knowing the exact biomechanical mechanism. In contrary, having understood cause and effect in detail, often uncovers even better insights and results. The old called that επιστήμη.

While the graph model is rich enough to model cause and effect effectively, such as when applied to QFD, this does not mean that a trained ANN easily does understand cause and effect. There exist prompting techniques that provoke *Chain-of-Thought* (CoT) reasoning, it is by counting CoT relations that an ANN learns to apply this kind of reasoning (Jin & Lu, 2024). Therefore, the argumentation is still based on statistical occurrences and does not use strict logic, let alone physical evidence. CoT does not avoid hallucinations; it is more like augurs that can distinguish and explain positive and negative signs in birds' flights. This activity and the pertaining rules were called *auspicium* by Roman augurs.

¹The reason adding the “Y” to “IS” unfortunately is of purely political nature.

Explainable AI

Humans actually have the same problem when using their brain to understand cause and effect. Most people must use various techniques, for instance, visual ideas, to produce logical evidence (Bessis, 2024).

Although logical thinking would be easy to implement with a graph model, there seem to be no examples of it in nature. The process is rather

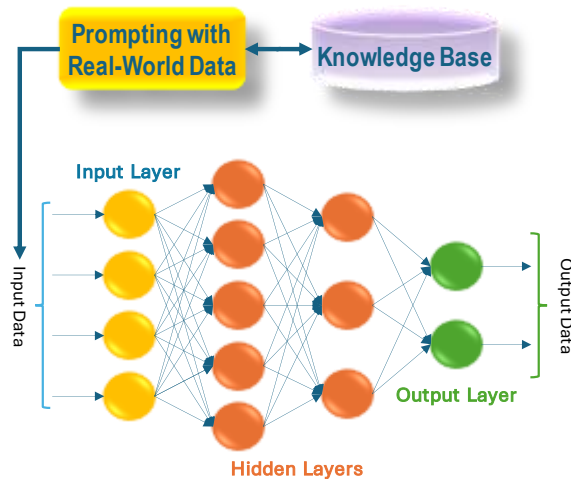
- a) The neural network hallucinates based on statistical observations;
- b) An explanation is given based on undisputable cause and effect.

It is difficult to imagine how explainable AI could do better. This is an argument against using statistical techniques such as SHAP (SHapley Additive exPlanations), a game theoretical approach, or LIME (Local Interpretable Model-agnostic Explanations), a method that fits a surrogate glass-box model to the decision space of any black-box model prediction. For an overview, see Dallanocce (Dallanocce, 2022).

These techniques use some sort of sensitivity analysis to “prove” that an AI decision is robust and not dependent on some specific prejudices. This is still statistics and not reasoning. It might be valuable to assess the quality of a training set but does not explain AI.

Explainable AI must be defined as a combination of observation-based, statistical processing, typically by an ANN, and subsequent logical verification by a reasoning engine based on cause and effect and logic rules. This is the way most humans do it. People observe first and then explain on the basis of facts.

Getting logical deductions that reflect physical facts and carrying out the cause-effect reasoning is not easy and often incomplete. Medical research, for example, relies much more on statistical tests than on cause-and-effect relationships, such as those obtained through genetic engineering or a complete understanding of biochemical processes in the living body. Nevertheless, even only incomplete reasoning can uncover hallucinations. Often reasoning requires much less detail than full knowledge processing. For instance, when judging actions proposed by an ANN-based *Advanced Driving Assistance System* (ADAS), they can be checked against physical facts and traffic rules to guarantee safety. A quick and rough examination can already reveal false assumptions and false reactions proposed.

Figure 1. *The Resource-Augmented Generation (RAG) Approach*

There has been hope that *Resource-Augmented Generation* (RAG) is an approach that should provide explainability, by reducing hallucinations. This approach consists of prompting an ANN by facts, taken from some knowledge base. Thus, the arrow scheme chain of ANN starts with some initial observations that are facts. The hope is that the ANN then produces less hallucinations. That works, but unfortunately only partially. There is still no convincing evidence that the response of the ANN reflects truth.

The RAG approach uses a standard ANN, in Figure 1 represented by a multi-layer perceptron without loops. It transforms input data, a vector of tokens, through several (a few hundred) layers into an output vector. The attention heads of the transformer are not represented (Lewis, et al., 2020). Nevertheless, there is no guarantee that the ANN produces thanks to RAG anything else than hallucinations.

Controlling Combinators

The basic characteristic of ANN is that there are no loops allowed from the input layer to the output layer. There are hidden layers in between but they do not provide feedback. This holds for *Feedforward Neural Networks* (FNN). *Recurrent Neural Networks* (RNN) are bi-directional ANNs that allow the output from some nodes to affect subsequent input to the same nodes (Gerven & Bohte, 2017).

In contrast, the natural brain, as well as Engeler's graph model of combinatory logic, have feedback loops by dendrites that freely can stimulate or attenuate responses. As in every traditional computer program, such loops can loop forever and damage neuronal reactions. Thus, the brain has mechanisms that Engeler modelled as *Controlling Combinators*. These are crucial for further developing artificial intelligence and better approximate human intellectual capabilities (Engeler, Neural algebra on "how does the brain think?", 2019).

Let X be some knowledge. The concept of *Control* involves a controlling operator \mathbf{C} which acts on a controlled object X by application $\mathbf{C} \bullet X$. Control means that the knowledge represented by X is completely known and described. It is a similar approach to establishing a fixpoint.

Accomplishing control in the graph model algebra can be formulated by:

$$\mathbf{C} \bullet X = X \tag{4}$$

The equation (4) is a theoretical statement, usually resulting in an infinite loop process. Remember, ANNs do not normally allow for loops. For solving practical problems, an approximation is normally needed for stopping the loop processing in time. In order to approximate X , an ordering relation must exist on knowledge that allows to identify proximity to a solution. This ordering relation is for knowledge the inclusion of sets of arrow terms.

A *Control Sequence* solves the *Control Problem*:

$$X_0 \subseteq X_1 \subseteq X_2 \subseteq \dots \subseteq X_n \subseteq \dots \tag{5}$$

Equation (5) is an infinite series of finite sets of knowledge, determined by (6):

$$X_{i+1} = \mathbf{C} \bullet X_i, i \in \mathbb{N} \tag{6}$$

starting with an initial X_0 . This is called *Focusing*. Focusing means that the knowledge represented by X is approximatively known and described as needed. Some details can be found in Engeler (Engeler, Neural algebra on "how does the brain think?", 2019, p. 299). The controlling operator \mathbf{C} gathers all knowledge that may help in the solution. Like a fixpoint combinator in combinatory logic, controlling operators are a structural element, not a single pair of observations and observed effect. The control problem is a repeated process of substitutions.

Continuous Training for AI

Controlling combinators can be used to build intelligent systems that learn continuously, because control sequences can provide continuous training based on empirical feedback received by some AI engine. The crucial point is to find a functional process for calculating the *Convergence Gap* that efficiently tells the intelligent systems how much it has learned. All computation must be executed on vectorized data using tokens. Such a system is suitable for implementing controlling combinators for a "mathematician," or a "violinist," as proposed by Engeler (Engeler, Neural algebra on "how does the brain think?", 2019).

While it is easy to calculate the convergence gap for the mathematician, once some reference is known – e.g., Wolfram|Alpha, see (Wolfram, 2023) – for the violinist, it is considerably more difficult. While for most violin pieces, reference recordings exist, it is currently not known how to measure the distance between a master recording and a student's attempt in music. Distance in AI (Sharma, 2024) always refers to Euclidean distance between two vectors, based on suitable tokens. But it is unknown which tokens to select, and how many. With today's methods, only decibels are measurable, such as for signal-to-noise. It is unclear how this helps the violinist to become better.

Intelligent Systems (ISY)

Euro Project Office has started a project to collect sample designs for ISY. It is freely available to interested parties against identification and authentication by a valid e-Mail (Fehlmann, Intelligent Systems, 2024). ISY can adapt to their environment.

Figure 2. Implementation of a Controlling Combinator

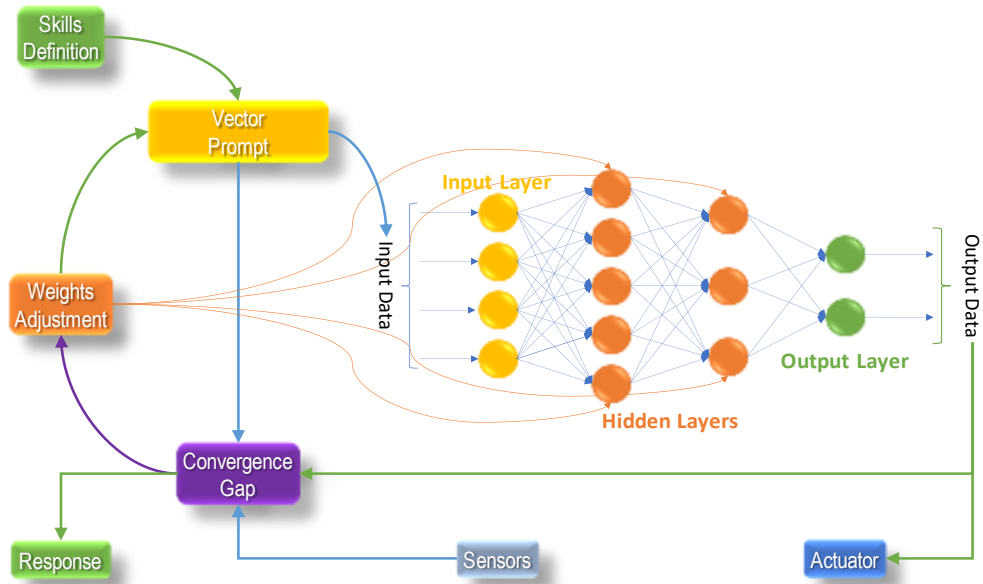


Figure 2 shows a design for continuous learning for an ANN. There are seven *Functional Processes* (FP) according to the ISO/IEC standard 19761 COSMIC (ISO/IEC 19761, 2019), needed to allow an ISY learning from empirical experiences gained by comparing the effects of output data with the reality influenced by the actuators and detected by sensors:

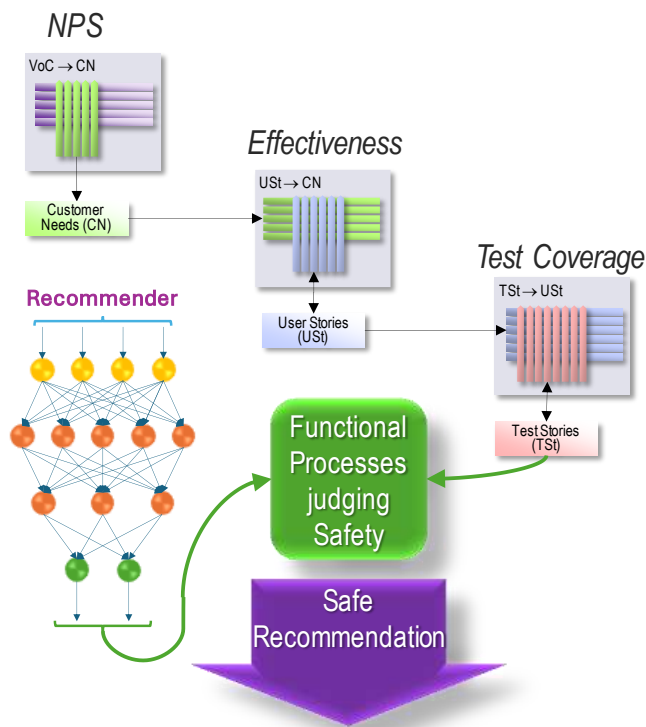
- The skills definition FP converts objects to token vectors;
- The vector prompt FP provides input data to some pretrained ANN;
- Output data FP triggers some action in the environment of the ISY;
- The sensors FP capture the effects of these actions;
- The convergence gap FP compares output data with action results;
- The weight adjustment FP trains the ANN accordingly;
- The response FP converts token vectors into objects.

All FPs use the same token vectors as the ANN as data. The track log from the convergence gap FP explains and controls all actions taken by such an ISY. This system could be used to train a computer implementation of Engeler's mathematician and violinist (Engeler, Neural algebra on "how does the brain think?", 2019).

AI under Control

A controlling combinator is not by itself a cause-effect control. It can explain how much an ANN has learned about reality and facts (Gnosis, γνώση) but not ascertain reasoning (Nous, νόος). The ANN still uses statistics when linking observations to concepts.

Figure 3. *Safe Recommendations by Autonomous Real-time Testing*



More stringent ISY compare their output data with knowledge gained from some strict knowledge-processing machine. An excellent candidate is testing. According to the principles of *Autonomous Real-time Testing* (ART) described in (Fehlmann, *Autonomous Real-time Testing – Testing Artificial Intelligence and Other Complex Systems*, 2020), tests can be described by arrow schemes; the same arrow schemes that an ANN processes. You can read equation (1) as a test case $x_j \rightarrow y$ with test data x_j , test data choice function j , and expected result y . Obviously, there is a huge gap in dimensions when comparing the few thousands of test cases, but an ANN is able to hallucinate about observations and concepts in some real world that can be tested.

The *Comprehensive QFD* shown in Figure 3 selects test cases to customer needs that were assessed with *Net Promoter Score* (NPS) (Fehlmann & Kranich, *Requirements Engineering for Cyber-Physical Products*, 2023). This is to avoid efforts spent on testing functionalities that are of no value for the customer. The effectiveness transfer function ensures that the choice of tests executed reflects customer needs, making this example of comprehensive QFD a strictly logical chain. The effectiveness matrix relies, like the test coverage matrix, on the number of data movements

identified according to the ISO/IEC standard 19761 (ISO/IEC 19761, 2019); thus, on real, measurable data. It detects hallucinations produced by the Recommender, making recommended actions safe, testable, and explainable. It achieves this by looking whether the recommendation is covered by some existing test. To make this design work, test cases must be written using the Recommender's token vectors.

Results

The referral to Homer and Aristotele in view of the graph model has shown that current AI raises wrong expectation if people believe an ANN does kind of reasoning. An ANN does Gnosis (γνώση) or hallucinate. Like the augurs of antiquity, but for similar reasons, explained by (Gigerenzer, 2007), these observations and hallucinations are more often hitting true points than not. If an ANN would be able to learn logic and reasoning, as is the goal of ARC Prize (Chollet, 2019), it would raise the problem of how to assure the quality of such reasoning. It would need exams like with humans.

The idea of testing potential hallucinations to ensure safety is more rewarding. There exist many such cases, where the combination of algorithmic rule-based programming with the power of generative AI can provide a whole class of innovative solutions called ISY.

Discussion and Further Research

Working with arrow schemes can be cumbersome and resource intensive. It is not recommended using this model for actual computing; it is a theoretical construct that opens the way to better understanding the possibilities and limitations of generative AI but not an assembly language for AI. However, it might be possible to programmatically construct dedicated, specialized nodes in an ANN, for instance for reasoning about observations and concepts.

The big obstacle is how to generalize observations into intuitive ideal objects. For instance, it seems unknown how to recognize observations of circular objects and link them to the ideal, mathematical concept of a circle, something human brains can do easily. Current AI systems cannot address unfamiliar problems outside their training data, despite extensive training on large datasets. AI lacks the ability to learn new skills (Chollet, 2019).

The graph model is useful in devising innovative solutions to these problems (Fehlmann & Kranich, A General Model for Representing Knowledge - Intelligent Systems Using Concepts, 2024). The key to teaching an ANN mathematical intuition is the choice function in arrow schemes. The choice must be some ideal mathematical concept, not grounded as usual in an observation in some real world. These arrow schemes can do mathematical reasoning based on intuitive, immaterial objects. The details of their implementation in an ANN are yet open; nevertheless, by complementing Gnosis (γνώση) with Episteme (επιστήμη) a big step forward towards ISY can be expected.

David Bessis, a French mathematician and AI entrepreneur, published a book about how mathematicians do their reasoning, and how children learn by curiosity and develop mathematical intuition (Bessis, 2024). The book reads to a computer scientist like programming instructions for how to enhance ANNs with choice functions towards mathematical objects and provides innovative ideas how to reconcile Gnosis (γνώση) with Techne (τέχνη).

Conclusions

It is recommended that AI engineers take courses in philosophy and in ancient cultures to better understand how today's AI is perceived and had been perceived over the centuries. Moreover, other disciplines than AI engineering often do have answers to the most pressing questions today: How to make AI intelligent?

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The Greenhouse in Space (GHIS) as STEM Educational Experience

By Enzo Bonacci*

*Artemis lunar settlement project has renovated the interest in space gardening, a topic addressed in 2011 by the section Human Spaceflight (HSF) of the European Space Agency (ESA) through the instructional project Greenhouse in Space (GHIS). Targeted to young teens (ages 12 to 14), the GHIS compared the growth of the *Arabidopsis thaliana* on Earth, at different latitudes and without sunlight, and in space (micro-g environment). The plants were seeded contemporarily in standard miniature greenhouses by around eight-hundred European schoolers, by the crew of the isolation experiment Mars500 (Moscow), and by the Italian astronaut Paolo Nespoli within the MagISStra mission on the International Space Station (ISS). Despite a toxic mold hazard alert on the ISS, the GHIS became a successful STEM experience, enthusiastically accomplished in sundry schools. Its heritage about microgravity plant research was formidable also outside Europe, notably in the US National Aeronautics and Space Administration (NASA). We illustrate how GHIS was implemented in numerous hands-on laboratories via learning-by-doing, and how such massive participation persuaded the space agencies to pursue further educational ventures and partnerships. We focus on the GHIS activity of 25 Italian pupils from the Scientific High School "Giovanni Battista Grassi" in Latina as a case study. The key reference is a talk delivered in the 98th annual congress of the Italian Physical Society at the University of Naples (September 17–21, 2012) together with a poster presentation in the international conference GIREP-EPEC 2011 at the University of Jyväskylä in Finland (August 1–5, 2011).*

Keywords: GHIS, ISS, ESA, HSF, EPO, NASA, ASI, STEM, HOL, ESD, NDVI, SEND, ICT, TRL, secondary school, educational project, *Arabidopsis thaliana*, Artemis

Introduction

Recognized as "a superstar of plant biology"¹, the *Arabidopsis thaliana* is object of accurate investigation since 1873 (Freed et al. 2025). It will be protagonist of the study LEAF² (Lunar Effects on Agricultural Flora) when the astronauts of Artemis III mission deploy a mini greenhouse on the Moon. Nevertheless, the information about one of the most inspiring scientific experiments and valid didactical opportunities ever devised around such plant, i.e., the "Greenhouse in Space" (acronym GHIS), is still partial and scattered. Why did it happen? This astonishing lack of specific literature on GHIS is probably due to the nature of participants: pupils too young to think about

*Teacher, formerly at Scientific High School "G.B. Grassi" of Latina, Italy.

¹<https://bit.ly/3QJm5pD>.

²<https://bit.ly/4cL132z>.

converting their experience into manuscripts or talks and secondary school teachers not used to academic research. This paper is meant as an exhaustive and organic survey on *GHIS*, reflecting on its long-term multifaceted impact, with the full awareness that the time span between the experiment (2011) and final version of the article (2026) represents a limitation. The *GHIS* was inaugurated in February 2011 (Figure 1) by the European Space Agency – Human Spaceflight (ESA–HSF for brevity) and summarized as follows: "The Greenhouse in Space is an educational project by ESA involving schoolchildren aged between 12 and 14 and ESA astronaut Paolo Nespoli at the International Space Station growing the same plants in similar small greenhouses for several months. The project started on 17 February 2011 with an event in four locations in Europe:

- Cité de l'espace in Toulouse France.
- ESA European Astronaut Centre, Cologne, Germany.
- ESA ESRIN, Frascati, Italy.
- Ciência Viva in Lisbon Portugal.

The students were connected to each other and to the ISS to speak with Paolo Nespoli, who planted and watered the first seeds live. Paolo is now using his specially-developed greenhouse in space to grow plants and make observations of the life cycle of a flowering plant. The schoolchildren are able to follow this with their own experiment on the ground, using a similar greenhouse and the same species of plant." (From ESA website³).

Figure 1. *The 2011 Official Logo of the Greenhouse in Space*



Source: <https://bit.ly/3B6Tymb>.

³<https://bit.ly/3TLHixl>.

Approximately eight hundred European schoolers, including pupils with Special Education Needs and Disabilities (SEND), joined the *GHIS* through STEM instructional projects based on Hands-On Laboratory (HOL) which reinforced the Education for Sustainable Development (ESD) for the critical role of plants in any ecosystems. The *GHIS* also augmented the Information & Communication Technologies (ICT) because students and teachers attended a live in-flight call with Paolo Nespoli⁴, and they were invited to send their photos and talk to each other on a Facebook page as well as by emailing the Human Spaceflight education team. The paper is organized as follows. In the first section we describe the initiative from the announcement (February 3, 2011) to the closing event (May 25, 2011), with mentions to the pioneering programme "Feeding our Future" and to the ESA missions *MagISStra* and *Mars500*. The second section analyzes the *GHIS* methodology by choosing, as a topical case study, the contribution from the Scientific High School "G.B. Grassi" of Latina (Italy), whose pupils seeded, watered and observed an *Arabidopsis thaliana* growing in a standard mini greenhouse (Figure 2). In the third section we discuss the scientific and educational implications of *GHIS* along a temporal range of 15 years. Most of the material about that trailblazing STEM activity comes from a thematical talk (Bonacci 2012) and a poster presentation (Bonacci 2011b). The legal framework and up-to-date literature are retrieved from current institutional and sectorial websites.

Figure 2. The 2011 ESA Education Kit for the Greenhouse in Space



Source: <https://bit.ly/4eFltcz>.

⁴<https://bit.ly/44ichaD>.

History of GHIS

The 2009 Forerunner ESA Programme "Feeding our Future"

In 2009, the European Space Agency – Human Spaceflight launched the preparatory campaign "Feeding our Future: Nutrition on Earth and in Space", examining food as a vital part of life on Earth and in space. In the ESA's explanatory page⁵, the HSF clarified that the programme, available in 13 languages (namely: Český, Dansk, Deutsch, English, Español, Ελληνικά, Français, Italiano, Nederlands, Norsk, Português, Suomi, Svenska) and presented by ESA Life Scientist *Nicole Sentse*, "shows why we need food in the first place and what it represents in our culture and daily living. The video illustrates how our bodies process food as a source of energy and building materials. It looks at the importance of good nutrition for a healthy life and what can happen without it, whether here on Earth or in space. The programme also looks at research for preserving and growing food for long flights, as well as valuable technology for future food supplies on Earth, where climate change and population growth are global challenges. New techniques developed for space missions can help to feed hungry people on our planet. The DVD has a duration of 35 minutes and can be downloaded as a high-resolution movie (417 MB). A Teacher's Guide and a User's Guide are also available for download." In addition, the ESA–HSF's Director *Simonetta Di Pippo*⁶ expounded that: "Food and nutrition are a fundamental part of our daily lives, not only because we need energy and nutrients to stay alive, but also because they are the basis of our culture and way of life. The ancient Romans used to say 'mens sana in corpore sano' (healthy mind in a healthy body), a saying that is even more meaningful nowadays as it emphasises the importance of food and nutrition for a healthy life style – especially for the younger generation. I am therefore pleased to introduce to European educators and students, the programme 'Feeding our Future – Nutrition on Earth and in Space'. The programme deals with the topic of nutrition from an inspirational perspective – space travel. Astronauts on board the International Space Station must stay healthy to be able to cope with the demands of life in space. Long term space exploration requires advanced technologies in several different fields, including life support systems for astronauts. Europe contributes a great deal to the life support system research effort and food technology is an important focus. So one of the next big questions is 'what will be for dinner on the Moon?' Space – like nutrition – is an interdisciplinary topic because of its scientific, technological, cultural and emotional values. It is therefore an ideal and inspirational subject to engage and provide curriculum related material for European students. One of the missions of the ESA Directorate of Human Spaceflight is to bring the fascination of human spaceflight and exploration to our youth. Education is part of the intangible benefits of our programme that contribute greatly to the establishment of a knowledge-based

⁵<https://bit.ly/45ppQVF>.

⁶<https://bit.ly/494CHis>.

society in Europe. I wish all teachers and students a pleasant view and work in the classroom." (From ESA website⁷).

The 2010-2011 ESA Missions Committed with GHIS

The *GHIS* was tested in the microgravity of an orbiting laboratory and in absence of sunlight. Such extreme environments were provided, respectively, by two pivotal 2010–2011 ESA missions:

- *MagISStra*, 159 days on the International Space Station⁸ (Figure 3);
- *Mars500*, 520 days in an isolation chamber in Moscow⁹.

Ground-based drop facilities and any other experimental setup for domestic microgravity, alternative to the International Space Station, were excluded for the long duration of the plants' growth.

Figure 3. Astronaut Paolo Nespoli and ISS Crew in December 2010



Source: <https://bit.ly/4erdZbB>.

⁷<https://bit.ly/4q6xAUU>.

⁸<https://bit.ly/40vhYiT>.

⁹<https://bit.ly/4kgoWiO>.

The 2010 Preliminary Greenhouse Test by Paolo Nespoli

Onboard the ISS module Columbus, Paolo Nespoli performed an illumination test¹⁰ within the operation "Greenhouse", supported by the Education Payload Operations¹¹ (EPO) and by the Norwegian USOC (Basit 2012), on December 26, 2010.

The 2011 GHIS Announcement by ESA-HSF

On February 3, 2011, the European Space Agency – Human Spaceflight Education (ESA–HSF for short) announced the project Greenhouse in Space (GHIS) as follows¹²: "It's a small greenhouse for space voyagers – and for you. Paolo Nespoli has a special greenhouse with him at the International Space Station and he's inviting young science enthusiasts to conduct an experiment with him. *Instructions are now online!* Growing plants in space will be crucial for the astronauts of the future. When flying to Mars or even further, it will be necessary to produce fresh food onboard and become partially self-sufficient. Setting up greenhouses on the Moon, Mars or other planetary bodies will also be an important part of future exploration missions. Greenhouses also provide oxygen and bring some life to the bleakness of space. Caring for plants is a good way to maintain memories of Earth and an enjoyable way to pass time during the long and possibly boring interplanetary cruise. Plants aboard the ISS – There is no danger of boredom during Paolo's MagISStra mission, as it will be packed with activity and science. The 'Greenhouse in space' project, proposed and conceived by ESA's Directorate of Human Spaceflight, is not only a scientific experiment but also an educational opportunity for schoolchildren aged between 12 and 14. Paolo will use a specially-developed greenhouse in space to grow plants and make observations of the life cycle of a flowering plant. The schoolchildren will be able to follow this with their own experiment on the ground, using a similar greenhouse and the same species of plant. The experiment starts with watering of some thale cress (*Arabidopsis thaliana*) set up in the International Space Station's Columbus laboratory. The children will start their own ground experiments at the same time. Paolo will take still images of the growth cycle and video recordings of key steps in the germination of the plants and post them on the MagISStra website. The participating children will be able to compare the space experiment with their ground experiment. The young scientists on the ground and Paolo in orbit will follow the growth cycle of their flowering plants for about 10 weeks. The children will be encouraged to exchange their observations with each other over this period, creating a Europe-wide network that enables one experiment to link young scientists together in a special way. Schools who wish to participate in this experiment can order their mini greenhouse ground kits from the ESA's Human Spaceflight education website, where there are limited numbers available. [...] The children will be invited to send their end results and observations to the

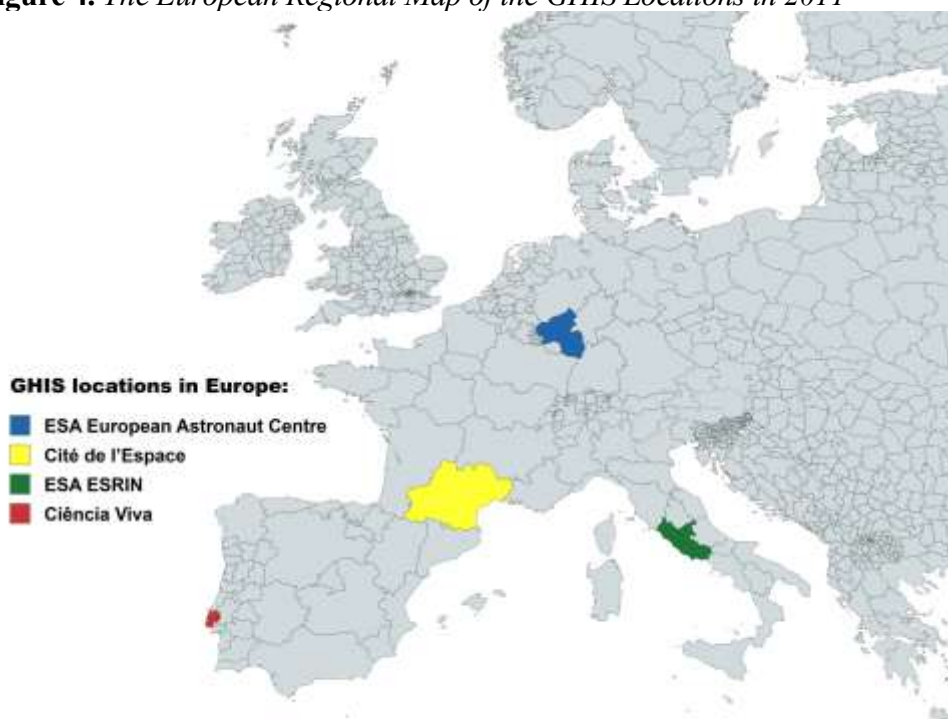
¹⁰<https://bit.ly/3L1DBDc>.

¹¹<https://bit.ly/4jBridA>.

¹²<https://bit.ly/4ipZ0kB>.

ESA Human Space Flight education team, who will create a final lesson online for download by other schools and teachers. The experiment will be launched on 17 February 2011 with a live event linking together nearly 750 children in four locations in Europe: the European Astronaut Centre in Cologne, Germany¹³; ESRIN in Frascati, Italy¹⁴; Cité de l'Espace in Toulouse, France¹⁵; and Ciência Viva – Agência Nacional para a Cultura Científica e Tecnológica in Lisbon, Portugal¹⁶. Paolo will of course participate in the event from the Space station which will have its own miniature greenhouse." Let us notice how the *GHIS* project was accomplished in different European microclimates (Figure 4).

Figure 4. *The European Regional Map of the GHIS Locations in 2011*



Source: <https://bit.ly/3YFX9jE>.

GHIS Inauguration by ESA-HSF

On February 17, 2011, *GHIS* started with circa eight hundred gardeners on Earth (above the initial estimate of 750) and one in space: "ESA's 'Greenhouse in Space' educational project began yesterday in four locations throughout Europe and on the International Space Station. This unique undertaking involves schoolchildren and ESA astronaut Paolo Nespoli growing the same plants in similar small greenhouses for several months. Growing plants is essential for us all. They not only provide food, but they are also beautiful and relaxing. And they can be educational: the Greenhouse in Space project offers European

¹³<https://bit.ly/3IafwIq>.

¹⁴<https://bit.ly/4q7CHV1>.

¹⁵<https://bit.ly/3YoxdJe>.

¹⁶<https://bit.ly/3N60ZzV>.

children aged 10–16 the chance to compare plants grown on Earth with those in space. More than 800 children are now space gardeners, asking burning questions such as 'How do plants know where up and down is in microgravity?' and 'How difficult is it to sow seeds in space?' Together with Paolo Nespoli, ESA's astronaut on the International Space Station, they will now discover the answers to these questions with their own experiments. Thursday was seeding day – The project was launched yesterday in France, Germany, Italy and Portugal, along with Paolo on the Station. The children and teachers linked up via video, learning how to assemble their own greenhouses and plant the *Arabidopsis* seeds. Sowing was not easy because of the minuscule seeds, but the choice of plant was far from random. *Arabidopsis* has already proved itself to be a hardy grower in space and, even more importantly, it self-pollinates – essential in the absence of pollinating insects in space! The students in Cologne were also treated to an impromptu appearance by Alexander Gerst, one of ESA's newest astronauts. And in Italy, there was a special space connection: part of the audience were students from Paolo's old school. Message from Space – Paolo joined the children in the afternoon by video for a 20-minute call from space, showing us his space-qualified greenhouse and watering the seeds. He demonstrated that simple procedures on Earth such as watering is extremely complex and possibly dangerous in weightlessness. Paolo kindly answered several questions from children in the different countries in a rare opportunity – it's not every day you get to speak to an astronaut in space. Now the children and Paolo are eagerly following the growing plants in this 15-week experiment. The results will be posted as an online lesson in ESA's web pages once the data from the 800 greenhouses on Earth have been compared to Paolo's experiment." (From ESA website¹⁷).

Mixed News from the ESA's Missions

In March 2011, the mission MagISStra interrupted the *GHIS* for the presence of a dangerous fungus, whilst the *Arabidopsis* plants kept growing well at *Mars500*. ESA clarified that: "Gardens are always a source of surprises. After three weeks of steady growth in space under the watchful eye of the ESA astronaut Paolo Nespoli, the baby space plants of the Greenhouse in Space project have found a new – and unexpected – travelling companion: fungus. The International Space Station (ISS) ecosystem is a particularly delicate one. Whereas some fungus does not cause much harm to earthly plants or humans, the balance of the closed systems in the Station could be compromised. It is known that spaceflight reduces the crew's immune systems, their ability to fight off infections, and once safety experts had confirmed that a fungus was growing in the greenhouse, the unavoidable decision was made to carefully remove the greenhouse from the ISS, thus avoiding any probability of causing any harm to the astronauts. The *Arabidopsis* plants, already having proved themselves as a hardy grower in space, seemed to grow very well despite the uninvited hitch-hiker on board. Paolo was the first one to remark that simple procedures on Earth are extremely complex and possibly dangerous in

¹⁷<https://bit.ly/4iNbxyr>.

weightlessness. 'Part of the experiment was indeed a success: we were able to grow the plants and observe them.' Even though some experiments can go wrong, Paolo said, 'This is a lesson to be learned that we can leave to the future astronauts. I'm sure they will get even better at it.' From real Space Station to virtual Mars spacecraft – The Greenhouse in Space education project moves on and encourages participating students throughout Europe to continue their experiments and monitor their plants even more closely. Now it is time to compare their greenhouses with the martian ones, as the crew of Mars500 found four of these little greenhouses packed in their lander module with all other cargo. Now they are carefully growing the same plants in their spacecraft-like modules and the results are coming in." (From ESA website¹⁸).

The GHIS Closing Event

On May 25, 2011, the *GHIS* closing event was celebrated as follows: "Harvest time for the little greenhouses–ESA's high-flying 'Greenhouse in Space' educational venture began in February with a live link to the Space Station and four events around Europe. Now, after three months, the project has finished in Lisbon – and aboard a virtual Mars spacecraft. More than 800 children around Europe took part in the Greenhouse in Space project with varying results: some of the *Arabidopsis* seeds in the miniature greenhouses grew well, but some did not. Most importantly, *Arabidopsis* proved itself to be a hardy grower in space. Its short life cycle from seed to seed, small size and ability to self-pollinate make *Arabidopsis* an ideal plant to grow in space. The greenhouse aboard the International Space Station unfortunately developed a potentially hazardous fungus. Since the Station's ecosystem is particularly delicate, it was decided to dispose of it. Whereas some fungi are quite harmless to earthly plants and humans, the balance of the 'closed' systems in the Station could not be risked. The crew of the Mars500 simulated mission to the Red Planet began their greenhouse experiment at the same time as ESA astronaut Paolo Nespoli started his on the Station. They set up three greenhouses and the results were very encouraging: some plants completed the full cycle. [...] Thank you, Lisbon! – The project's closing event was held in Lisbon, Portugal, at the Ciencia Viva science centre. Ciencia Viva invited 173 children and 20 teachers from eight schools from all over Portugal to present their findings on 12 May. Duarte Lopes elementary school in Benavente and Abel Salazar secondary school probed deeper by investigating how well *Arabidopsis* grows in different soils. Students even tried growing their seeds in gelatine – and the seeds germinated. Marcelino Champagnat school in Lisbon kept two greenhouses under the same conditions but withheld fertiliser from one. The school was awarded the first prize for their presentation and were given a Space Garden kit to try out some of their new ideas. Students from Duarte Lopes elementary school suggested using larger seeds and plants that are less sensitive to wide temperature changes. They concluded that such experiments are important for gaining knowledge for

¹⁸<https://bit.ly/4iIA5sm>.

space missions. They found that one experience leads to many others, and that learning is a continuous process." (From ESA website¹⁹).

The Aftermath

The ESA invited all the other European participants to submit their findings by the end of June 2011. The Italian secondary schools respond to local administrations (regional or provincial, depending on their curricula) and the Province of Latina²⁰ (manufacturing hub in southern Lazio²¹) was represented in the *GHIS* by the Scientific High School "G.B. Grassi" whose students sent their "Greenhouse results" on May 27, 2011. Anyway, the *GHIS* did not terminate in May 2011 but lasted until the end of the *Mars500* mission, whose crew were able to grow their seeds to maturity as well as harvesting new seeds. Their results were summarized by Romain Charles – one of the crew members: "We started the Greenhouse in Space experiment with 4 small greenhouses on the 17th of February 2011. We sowed a total of 36 seeds. After one month, only 5 sprouts appeared in 2 of the greenhouses. Then I took the decision to prepare the 2 other greenhouses with a new soil and 16 new seeds. After a few weeks, we had a total of 7 different plants but some of them were already dying. After 12 weeks (3 months), the pods of the only surviving plant opened and I could harvest its seeds. I prepared a new greenhouse (new soil) for the seeds newly produced to check if our production was sustainable. Unfortunately, after 3 weeks, no sprout appeared." (From ESA website²²).

Methodology of GHIS

A Case Study: The GHIS by the Italian High School "G.B. Grassi"

We focus on the educational project "A greenhouse in space" by which the Scientific High School "Giovanni Battista Grassi" of Latina²³ (Miltiadis 2020) signed up the *GHIS* proposed by ESA in 2011. Hosting the Planetarium "Livio Gratton", a mighty driver of STEM projects (Bonacci 2016a, 2016b) and participatory science (Bonacci 2020a), that secondary school²⁴ has always been connected to the ESRIN of Frascati and to "Frascati Scienza" (Bonacci 2018b, 2020b). The short distance (only 55 km) and excellent welcome organization fostered guided tours and solo visits in the decade 2010-2020. The consequent peak of enrolment in university faculties related to space exploration²⁵ confirmed that both STEM career knowledge and interests are influenced by society at large (Blotnicky et al. 2018) and benefit from the collaboration with multi-stakeholders (Jiménez-Iglesias et al. 2016). Being the sole school to register in

¹⁹<https://bit.ly/3DFpsrq>.

²⁰<https://bit.ly/4spx0mN>.

²¹<https://bit.ly/4js9tO2>.

²²<https://bit.ly/41Qp6pY>.

²³<https://bit.ly/4jsESQm>.

²⁴<https://bit.ly/443wGNk>.

²⁵<https://bit.ly/3MWa9PB>.

GHIS, the "G.B. Grassi" represented the whole Province of Latina, a territory deeply studied²⁶ by geologists (Cappucci et al. 2024) for its peculiar coastal geomorphology (Perazzotti & del Valle 2025).

Project Design and Participants

When ESA ESRIN called for the *GHIS* applications in Italy, the Director of the Planetarium of Latina responded immediately with an *ad hoc* project based on *hands-on laboratory* and summarized in the Table 1.

Table 1. *The 2011 GHIS Project of the School "G.B. Grassi" in Latina (Italy)*

Title	A greenhouse in space (original title in Italian: "Una serra nello spazio").
Aims	Seeding, watering and observing the growth of a plant in the laboratory with reference to the results obtained in space (mission MagISSTra) and on Earth (in the isolation experiment Mars500 and in other schools).
Goal	Spotting the differences between the terrestrial and the space (micro-g) environment about the evolution of a low technology readiness level (TRL 4) botanic process.
Materials	An ESA's standard miniature greenhouse (i.e., a growth chamber with medium perlite, a transparent cover, a transparent cap, a black cut out piece of foam, a seed bag of <i>Arabidopsis thaliana</i> with fertilizer), a watering beaker, a magnifying glass, a pair of thin forceps, some filter paper to place the seeds on, and a large sunny window.
Tools	EPO Educational Kit P/N 309348 ²⁷ for ESA's Greenhouse in space
Project Manager	Enzo Bonacci, Teacher of Mathematics and Physics, Director of the Laboratory of Physics and of the Planetarium "Livio Gratton" in Latina.
Project Team	Twenty-five students aged 14, sixteen girls and nine boys, from the Scientific High School "Giovanni Battista Grassi" in Latina (Italy).

Source: <https://bit.ly/4mkqxWa>.

On February 9, 2011, the School Executive Committee urgently approved the educational project "Greenhouse in Space" (Italian title: "Una serra nello spazio") appointing the Director of the Planetarium as Manager who, subsequently, selected 25 motivated pupils (Figure 5). Sixteen of the twenty-five *GHIS* high schoolers were girls, breaking the gender stereotype of Science for secondary students (Makarova et al. 2019). The percentage of schoolgirls (64%) was stunning if compared, e.g., to the 35% share of female STEM graduates recorded in 2024 by the UNESCO Institute for Statistics²⁸.

²⁶<https://bit.ly/44Tcj8F>.

²⁷<https://bit.ly/3FooEYH>.

²⁸<https://bit.ly/45JctQM>.

Figure 5. The 25 GHIS Students from "G.B. Grassi" of Latina (Italy)



Source: <https://bit.ly/3IRV3IJ>.

Data Collection and Analysis

Since the three *GHIS* subjects (Astronomy, Biology, Physics) were curricular in the Italian Scientific High School²⁹, there was no need for special training. Between February 10 and 16, 2011, the students watched the ESA'S 2009 DVD "Feeding our Future: Nutrition on Earth and in Space", familiarized themselves with the concept of microgravity³⁰ and with the *Arabidopsis thaliana* (plant also known as *thale* or *mouse ear cress*), studied the ISS as the home of humanity in space and the significant contribution Italy gave to its construction (ASI website³¹). On February 17, the *GHIS* team (i.e., the kids and the Project Manager) linked up via video to Paolo Nespoli on the ISS, learning how to assemble their own greenhouses and plant the *Arabidopsis* seeds³². They opened the EPO's kit and placed the medium into the growth chamber, mixing it well with the fertilizer; they poured 40 ml of water onto the growth medium; they shook the growth chamber to ensure water was well distributed and they placed the cut out black foam pad over the top of the wet growth medium; they opened the seed container and, using magnifying glasses and thin forceps, separated out few *Arabidopsis* seeds onto a small piece of filter paper; they placed the seeds inside one of the holes in the black foam and pressed down into the growth medium so that it covered the seeds, repeating this till they had planted seeds in all 7 holes; then they remove the black cut out foam, took the transparent plastic cover and placed it over the entire white growth chamber; they put the cap on it and placed their growth chamber near the sunny windows of Physics Lab. From February 18 until March 16, the students monitored the germination of their seeds and watered when needed, keeping the substrate moist without causing it to be waterlogged. They also placed a thermometer inside the greenhouse and annotated the temperatures, week by week, fifteen times. The ten weekly entries of the observations' form, provided by ESA both in Italian (Figure 6) and in English (Figure 7), were:

- Height (mm);
- Temperature (°C);
- Number of internodes;
- Color (red-green-yellow);
- Plants problems;
- Flowers (yes/no);
- Water (mls);
- Estimated hours of daylight;
- Condensate (yes/no);
- Notes.

²⁹<https://bit.ly/4vQ4sVh>.


³⁰<https://bit.ly/3xSkukD>.

³¹<https://bit.ly/3R8SmS4>.

³²<https://bit.ly/4kOAr2p>.

Figure 6. The GHIS Report from Latina on ESA's Form in Italian

ARABIDOPSIS: OSSERVAZIONI:




Settimana	Altezza (mm)	Tempo °C	N° di Internodi	Colore			Problemi alla Pianta	Fiori, Sì/no	Acqua ml/s	Ore Stimolate di Luce del Sistema	Condensa Sì/no	NOTE
				Red	Verde	Giallo						
1	0	13-18	0					NO	40	7	NO	19/02/2011
2	10-20	14-19	0		X			NO	5	8	NO	24/02/2011
3	20-30	14-19	1		X			NO	5	8	NO	04/03/2011
4	40-50	15-20	3		X			QUASI	5	9	NO	11/03/2011
5	60-80	15-20	5		X			SI	5	9	NO	18/03/2011
6	80-100	16-21	6		X			SI	5	10	SI	25/03/2011
7	100-120	16-21	7		X			SI	5	10	SI	01/04/2011
8	120-130	17-22	8		X			SI	5	11	SI	08/04/2011
9	130-150	17-22	10		X			SI	10	11	SI	15/04/2011
10	150-160	18-23	11		X			SI	10	12	SI	22/04/2011
11	160-170	18-23	12		X			SI	10	12	SI	29/04/2011
12	170-180	19-24	13		X			SI	10	13	SI	06/05/2011
13	180-190	19-24	14		X			SI	10	13	SI	13/05/2011
14	190-200	20-25	15		X			SI	10	14	SI	20/05/2011
15	200-210	20-25	15		X			SI	10	14	SI	27/05/2011

European Space Agency

Source: <https://bit.ly/3TuZ4oA>.

Figure 7. The GHIS Report from Latina on ESA's Form in English

ARABIDOPSIS OBSERVATIONS:



Week	Height (mm)	Temp °C	N° of internodes	Colour			Plants Problems	Flowers Yes/No	Water ml/s	Estimated Hours of day light	Condensate Yes/No	NOTES
				Red	Green	Yellow						
1	0	13-18	0					NO	40	7	NO	2011-02-19
2	10-20	14-19	0		X			NO	5	8	NO	2011-02-24
3	20-30	14-19	1		X			NO	5	8	NO	2011-03-04
4	40-50	15-20	3		X			NEARLY	5	9	NO	2011-03-11
5	60-80	15-20	5		X			YES	5	9	NO	2011-03-18
6	80-100	16-21	6		X			YES	5	10	YES	2011-03-25
7	100-120	16-21	7		X			YES	5	10	YES	2011-04-01
8	120-130	17-22	8		X			YES	5	11	YES	2011-04-08
9	130-150	17-22	10		X			YES	10	11	YES	2011-04-15
10	150-160	18-23	11		X			YES	10	12	YES	2011-04-22
11	160-170	18-23	12		X			YES	10	12	YES	2011-04-29
12	170-180	19-24	13		X			YES	10	13	YES	2011-05-06
13	180-190	19-24	14		X			YES	10	13	YES	2011-05-13
14	190-200	20-25	15		X			YES	10	14	YES	2011-05-20
15	200-210	20-25	15		X			YES	10	14	YES	2011-05-27

European Space Agency

Source: <https://bit.ly/4eIKhJS>.

Development

On March 17, the *GHIS* team learned about the abrupt interruption of the test in the *micro-g* environment, due to *fungus* in the EPO's kit on ISS, and followed the three-level safety containment packaging by Nespoli³³ (with mask, glasses, plastic bags, insulating tape, and gloves) as waste of *mild* toxicity level (tox 2) to send back to Earth in a cargo spacecraft. On March 18, the students changed place from the Physics Lab to the Biology Lab (Figure 8) for better sunlight; after comparing their early results with those from *Mars500* (Figure 9), they kept noting down the features of their growing plants (Figure 10).

Figure 8. *Observing the Plant at School After One Month, on March 18, 2011*



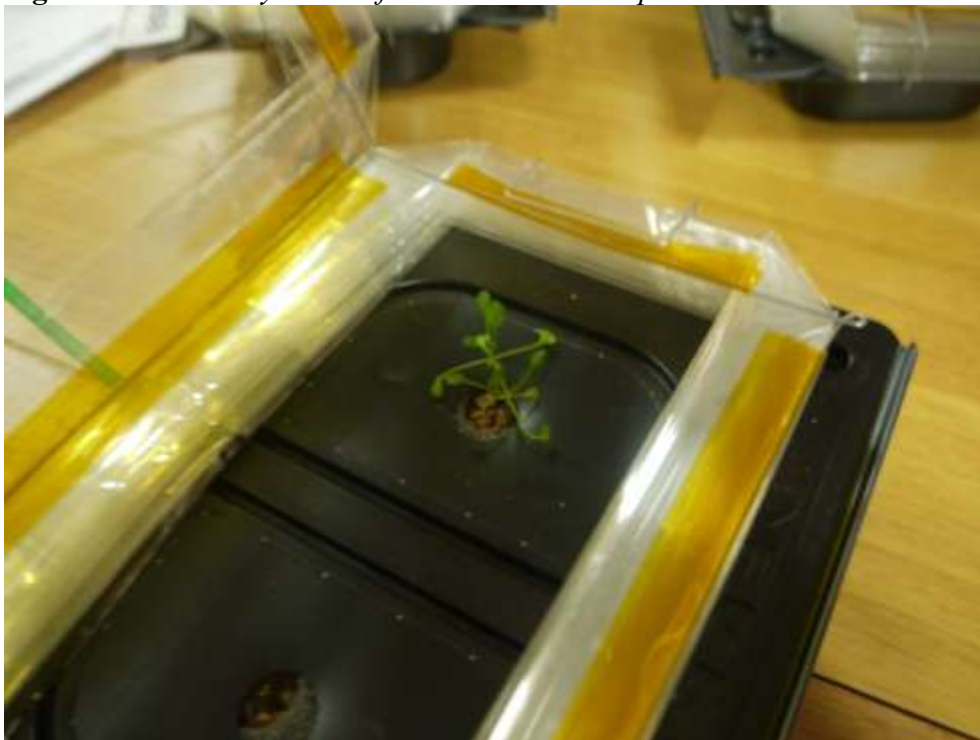
Source: <https://bit.ly/3IRV3IJ>.

After attending remotely the *GHIS* closing event celebrated in Lisbon³⁴, the pupils finished filling out the forms for the final report "Greenhouse results from Latina". In August 2011, the Project Manager popularized the Latina's *GHIS* contribution in a poster session at the University of Jyväskylä (Bonacci 2011b) and, in September 2012, he illustrated the Latina's *GHIS* experience in a talk at the University of Naples (Bonacci 2012).

³³<https://bit.ly/3DuFSD8>.

³⁴<https://bit.ly/3DFpsrq>.

Figure 9. *GHIS Early Results from the Isolation Experiment Mars500*



Source: <https://bit.ly/44xxWKB>.

Figure 10. *Observing the Plant at School After Two Months, on April 22, 2011*

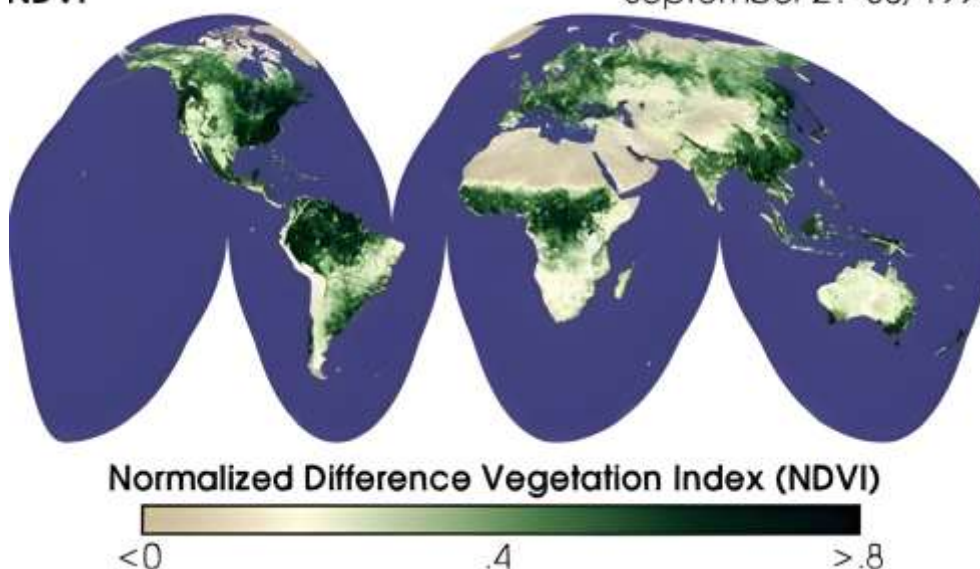


Source: <https://bit.ly/3IRV3IJ>.

Findings

The *GHIS* brought research into the classroom (Nistor et al. 2019) by adopting what we today call the STEM best practices (Kasza & Slater 2017) and ensured optimal conditions to improve the girls' STEM self-efficacy (Wieselmann 2019). Latina's kids were the first to notice that the color of the plants seemed sensitive to the latitude and decided autonomously to confront via email with Italian and foreign schools to find statistical evidence to their empirical observation. From the data of twenty European teams, they verified that the average shift from green to yellowish had happened first in Portugal (7-8 weeks), soon after in Italy (8-9 weeks), then in France (9-10 weeks), and finally in Germany (12-13 weeks). Latina's GHIS team was congratulated by the Provincial Head of the International Year of Chemistry, *Francesco Giuliano*, for carrying out constructivist didactics (Giuliano 2015). While presenting the GHIS at the University of Jyväskylä (Bonacci 2011b), the Team Manager was advised that Latina's high schoolers might have unknowingly grasped of a broader trend (Figure 11) tracked through the satellite scrutiny of the Normalized Difference Vegetation Index (NDVI) and fairly popular in in Finland at the time³⁵: the "Northern Greening".

Figure 11. Satellite Maps of Vegetation over the Entire Globe in 1999
NDVI September 21–30, 1999



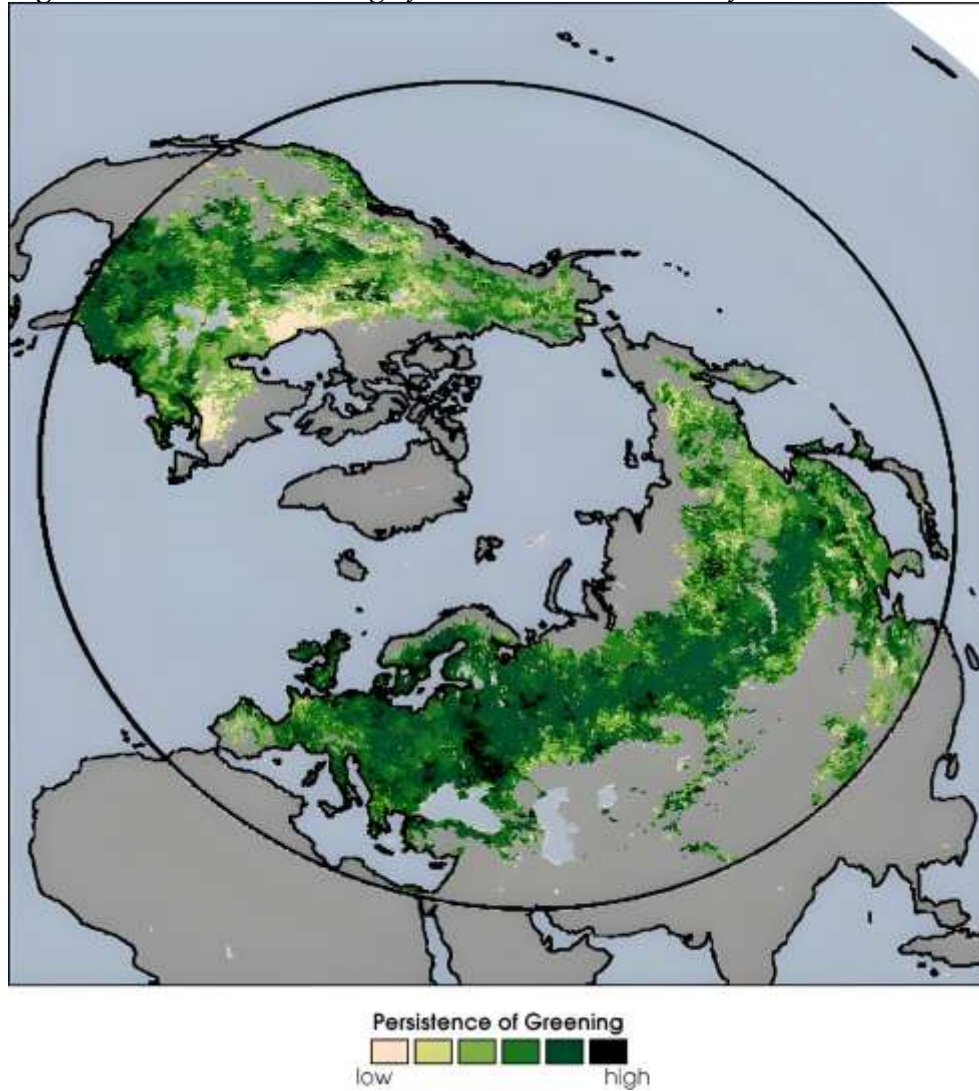
Source: <https://bit.ly/4d23fRW>.

The *Northern Greening* (Figure 12) was unveiled as follows: "NASA satellite data suggest that for more than two decades there's been a gradual greening of the northern latitudes of Earth. Researchers confirm that plant life seen above 40 degrees north latitude, which represents a line stretching from New York to Madrid to Beijing, has been growing more vigorously since 1981. One suspected cause is rising temperatures possibly linked to the buildup of greenhouse gases

³⁵<https://bit.ly/48EckiO>.

in our atmosphere. Over this same time period, parts of the Northern Hemisphere have become much greener and the growing season has increased by several days. Further, Eurasia appears to be greening more than North America, with more lush vegetation for longer periods of time." (From NASA website³⁶).

Figure 12. *Northern Greening by NASA Earth Observatory in 2001*



Source: <https://bit.ly/4uuHL7l>.

Since *Northern Greening* was a phenomenon which the Italian pupils had never heard about, their insight could not be an elaboration of previous knowledge but was due to an accommodation of their mental structure. Where did the STEM mindset³⁷ of those kids come from? It presumably derived from intuition as developable skill (Miskioğlu et al. 2024), collaborative partnership (Reid-Griffin et al. 2023), and perseverance (Shechtman et al. 2018).

³⁶<https://bit.ly/4tSMqAj>.

³⁷<https://bit.ly/4ePBD5p>.

Implications of GHIS

Scientific Implications

After the *GHIS* experience, ESA dedicated a webpage³⁸ to research in space, and on parabolic flights, about the *Arabidopsis thaliana* acknowledging that "Growing plants for food in space and on other planets will be necessary for exploration of our Universe". Today we know that such plants germinate in diverse lunar regoliths (samples from Apollo 11, 12, and 17) but their growth is slow and affected by severe stress morphologies (Paul et al. 2022) so that we need to find efficacious mediums for horticultural crops on the Moon. For instance, the *Arbuscular Mycorrhizal* fungi furnish the *Cicer arietinum* (chickpea), cultivated in lunar regolith simulant³⁹ (Atkin et al. 2026), with a powerful bioremediation. Suddenly, the *GHIS* mold accident accelerated the studies on the fungal responses in space environments named, collectively, "Astromycology". This recent research area (Simões et al. 2023) has considerably progressed from the 2012 Micro-6⁴⁰ investigation on *Candida albicans* by NASA⁴¹ to the 2024 microbial consortia for space biomining by ESA⁴²; the latter led to discovering that bacteria *Sphingomonas desiccabilis* and fungi *Penicillium simplicissimum* under microgravity could potentially extract forty-four elements out of L-chondrite asteroidal material (Santomartino et al. 2026). Astromycology employs also terrestrial facilities, such as the ESA's Large Diameter Centrifuge⁴³ where the growth of fungal colonies is tested under double normal Earth's gravity. The enduring echo of *GHIS* induced ESA to launch, in April 2017, the *AstroPlant* as "a citizen science initiative that aims to inspire home-gardeners, schools, urban farmers and enthusiasts to nourish seeds selected by the MELiSSA⁴⁴ team. Data recorded via a smartphone app will be sent to ESA for processing." (From ESA website⁴⁵). The *GHIS* paved the way to modern microgravity plant research outside Europe too, especially by the National Aeronautics and Space Administration (NASA). In fact, on April 18, 2014, NASA launched the "Vegetable Production System" (Veggie) as "a space garden residing on the space station. Veggie's purpose is to help NASA study plant growth in microgravity, while adding fresh food to the astronauts' diet and enhancing happiness and well-being on the orbiting laboratory." (From NASA website⁴⁶). Analogously, on April 18, 2017, NASA launched the "Advanced Plant Habitat" (APH) as "the largest, fully automated plant growth research facility that is used to conduct plant bioscience research on the International Space Station (ISS). It occupies the lower half of the EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Rack and one powered International Sub-rack Interface Standard (ISIS) drawer, providing a fully enclosed, closed-

³⁸<https://bit.ly/44f9YVG>.

³⁹<https://bit.ly/4bvPII5>.

⁴⁰<https://bit.ly/4sIMe5P>.

⁴¹<https://bit.ly/3P1JK3R>.

⁴²<https://bit.ly/4ljR3E>.

⁴³<https://bit.ly/3MVg0Fd>.

⁴⁴<https://bit.ly/4leb0am>.

⁴⁵<https://bit.ly/3IcYGss>.

⁴⁶<https://bit.ly/44X0gHn>.

loop plant life support system with an environmentally controlled growth chamber designed for conducting both fundamental and applied plant research during experiments extending up to 135 days. The system requires minimal crew involvement to install the science, add water, and other maintenance activities." (From NASA website⁴⁷). In April 2026, the second successful stage⁴⁸ of Artemis program for a permanent human presence on the Moon⁴⁹ has invigorated NASA's endeavors to cultivate plants in extraterrestrial habitats (Fountain et al. 2026).

Educational Implications

We define *GHIS* as a STEM activity for entailing three different subjects (Kelley & Knowles 2016): Astronomy, Biology, and Science. Although missing one of its highest goals, i.e., a full comparison with the ISS experiment, the *GHIS* strongly opposed the low attractiveness of STEM studies (Nistor et al. 2018), with a passionate response from eight hundred students, with various SEND pupils (Ianes et al. 2020), and dozens of teachers. As highlighted by the organizers⁵⁰, *GHIS* sparked children's interest in science at an early age; the teacher *Paulo Fonseca* (Escola Básica D. Duarte, Viseu) exclaimed: "This was a unique occasion to talk to an astronaut and stimulate the appetite for science of our kids". Even the unwelcome fungus onboard the ISS turned into an instructional opportunity, letting the pupils realize that laboratory tests can be affected by accidents neglected by simulations (Bonacci 2025) and that virtual and hands-on laboratories may offer complementary affordances (Kapici et al. 2019). The *GHIS* projects were implemented via *learning by doing* (Dewey 1916) in traditional laboratories (technology level TRL 4), triggering the emotional intelligence (Parker et al. 2004), and corroborating both the ICT (Gras-Velázquez 2016, 2017) and the ESD (Gras-Velázquez & Fronza 2020). The *GHIS* contribution from "G.B. Grassi" of Latina, the scientific high school hosting the Planetarium "Livio Gratton" (Bonacci 2011a, 2013), whose students were the first to observe and measure the persistence of *greening* at higher latitudes, was quite appreciated in the Section "Didactics of Physics" of the 98th Congress of the Italian Physical Society (September 17–21, 2012) at the University of Naples (Bonacci 2012) and in the annual conference (August 1–5, 2011) of the International Research Group on Physics Teaching (GIREP) & the European Physical Society – Physics Education Division (EPEC) at the University of Jyväskylä in Finland (Bonacci 2011b). The latter projected the young city of Latina⁵¹ on an international stage, so that the cosmonaut Walter Villadei went there in person to sponsor the school contest "Space for Your Future. The ISS: Innovatio, Scientia, Sapientia" in 2016 (Bonacci 2023). In conjunction with the start of the *GHIS* campaign, ESA potentiated the European Space Education Resource Office (ESERO⁵²); opened in 2006⁵³, such project has become the

⁴⁷<https://bit.ly/49pQmQ4>.

⁴⁸<https://bit.ly/4uh7NuJ>.

⁴⁹<https://bit.ly/4cO4Z1o>.

⁵⁰<https://bit.ly/4iNbxyr>.

⁵¹<https://bit.ly/4mKNJhg>.

⁵²<https://bit.ly/3HBG8lP>.

⁵³<https://bit.ly/4lO6Mpp>.

foremost path of supporting early years, primary and secondary education community in Europe. On the footprint of the *GHIS*, the Italian Space Agency (ASI) raised other instructional initiatives with the endorsement of astronauts as science ambassador (McNamee 2025), like the competition "YiSS – Youth ISS Science" publicized by Paolo Nespoli⁵⁴ (Rizzo 2022). In Spain, instead, the "Ignacio da Riva" University Microgravity Institute⁵⁵ advocated the "Europe to Space" program (EU2Space⁵⁶), a challenge tailored for university students from any major (Roibas-Millan et al. 2023) to "plan, design, solve, and put your hands on a real satellite that will fly to space" (from UARX website⁵⁷).

Conclusions

We have tried to revive the *Greenhouse in Space* (GHIS), whose memory was quickly fading away, by collecting, arranging, and evaluating documentary evidence of that grandiose project from both its organizers and participants. Promoted in 2011 by ESA–HSF, the *GHIS* was hugely run by schools of four European countries (France, Germany, Italy, Portugal) with more than 800 early adolescents observing the *seed-to-seed* life cycle of an *Arabidopsis thaliana* implanted in a standard miniature greenhouse. The same kit was employed in two parallel ESA missions (*MagISStra* on the ISS and *Mars500* in a Muscovite isolation chamber) to spot the differences among the plants grown naturally (European schools), in microgravity (ISS), and without sunlight (Russian Institute for Biomedical Problems). Unfortunately, the comparison with the ISS gardening experiment was interrupted by the formation of dangerous mold beside the astronaut's plant (toxicity level 2). The fungal contamination that occurred on the ISS did not stop the *GHIS* school projects and, as collateral beneficial effect, lifted the role of *Astromycology* in ameliorating the conditions for life support within hypothetical lunar stations. Actually, the *GHIS* was a tremendous STEM enrichment activity based on *learning by doing* in traditional laboratories (technology level TRL 4). The engaging and sustainable (Carroll et al. 2019) *GHIS* projects strengthened problem solving, critical analysis, teamwork, communication, and digital literacy, i.e., some of the soft skills requested by labour market (Holik & Sanda 2023). The *GHIS* maximized the STEM good practices by integrating the HOL (Bonacci 2026), the ESD (Bilgin et al. 2022), and the ICT (Lukychova et al. 2021) in innovative SEND-inclusive environments (Fortepiani & Marsh 2023). Additionally, the positive response of students usually unattracted by *Science* revealed the importance of stimulating the emotional intelligence of kids (Petrides et al. 2004) by involving other cognate subjects, such as *Biology* and *Astronomy*⁵⁸, and of nourishing their curiosity (Kowalski & Kowalski 2015) by using the Science Laboratories (Hofstein & Kind 2012). The Scientific High

⁵⁴<https://bit.ly/47XKf6a>.

⁵⁵<https://bit.ly/4qISWYZ>.

⁵⁶<https://bit.ly/4pHy2ru>.

⁵⁷<https://bit.ly/49qgHyB>.

⁵⁸<https://bit.ly/3GYXTqF>.

School "Giovanni Battista Grassi" in Latina, a dynamic⁵⁹ agro-industrial Italian province, joined the "Greenhouse in Space" with a team of twenty-five 14-year-old pupils (64% schoolgirls). Those high schoolers faced *GHIS* with expertise because, in spring 2011, the "G.B. Grassi" had already praxis of citizen science (Heigl et al. 2019) and STEM projects (Bonacci 2018a), propelled by the Planetarium "Livio Gratton" (Bonacci 2017). The presence of accessible and well-equipped Physics and Biology Labs was another driving factor in the success of the *GHIS* project from the "G.B. Grassi", that was divulged in national and international symposiums soon after the students had inferred, on a reasonable sample of data, a correlation between the plants' period of turning color and the tests' latitudes. Along with other ESA's educational projects⁶⁰, the "Greenhouse in Space" favored the inclusion of *Astronomy* in most European schools' curriculum (Percy 2005), tough rarely as standalone subject, to amplify many of the competences (Boon 2019) required in the *high-quality* STEM pedagogy auspicated by the European Education Area (EEA)⁶¹. Besides the strong instructional impact⁶², bridging the gap between advanced space missions and classroom education⁶³, the *GHIS* left a long-lasting scientific inheritance to ASI, ESA, and NASA. Nowadays, topical examples of the *GHIS* legacy are: the ENEA's HortSpace⁶⁴, a research initiative co-funded by ASI and focused on high-tech systems for cultivating plants in space; the "Adaptive Vertical Farm" (AVF⁶⁵), a spatial greenhouse devised by the startup Space V⁶⁶; the Greencube⁶⁷, a micro-garden of fresh vegetables built by the University "La Sapienza" of Rome⁶⁸ and installed in an ASI's mini-satellite⁶⁹ sent to 6000 Km from Earth on ESA's vector Vega-C⁷⁰; and NASA's LEAF⁷¹, a mini-greenhouse on the lunar surface to study how the plants *Arabidopsis thaliana*, *Brassica rapa*, and *Wolffia* grow in partial gravity and high radiation.

⁵⁹<https://bit.ly/4aJwoCa>.

⁶⁰<https://bit.ly/4pHCxCE>.

⁶¹<https://bit.ly/3L3Z7Vj>.

⁶²<https://bit.ly/4q9hPfO>.

⁶³<https://bit.ly/4srLMcF>.

⁶⁴<https://bit.ly/49rZnrM>.

⁶⁵<https://bit.ly/3HcWGA7>.

⁶⁶<https://bit.ly/45tJO1Y>.

⁶⁷<https://bit.ly/3LzpIld>.

⁶⁸<https://bit.ly/3NvWiiY>.

⁶⁹<https://bit.ly/49GpaO6>.

⁷⁰<https://bit.ly/3Z2c1J9>.

⁷¹<https://bit.ly/4tKKJoi>.

Remarks

The reader should not be surprised that the EPO Educational Kit P/N 309348⁷² was manufactured by a firm in Aprilia, a town 26 km north of Latina. In fact, the Province of Latina has a distinct agricultural propensity, with the largest number of farm workers in the Lazio region (slightly higher than Rome)⁷³. Latina is also the Italian second province (next to Milan) for number of employees in pharma companies, and the first for pharmaceutical exports (ahead of Milan)⁷⁴. On November 24, 2025, the Mayor Matilde Celentano signed a Memorandum of Understanding⁷⁵ with "La Sapienza" University⁷⁶ and Unindustria⁷⁷ to expand the chemical-pharmaceutical hub of Latina.

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⁷²<https://bit.ly/3FooEYH>.

⁷³<https://bit.ly/3Hwnskw>.

⁷⁴<https://bit.ly/3jbez6v>.

⁷⁵<https://bit.ly/4jsymJa>.

⁷⁶<https://bit.ly/4bkPA9q>.

⁷⁷<https://bit.ly/497imci>.

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