Worlds Beyond Our Sun: A Data-Driven Search for Potentially Habitable Exoplanets

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The search for habitable planets is a key focus in astrobiology, where data-driven approaches can help identify the most promising candidates. The study examines roughly 38,000 exoplanet entries from the NASA Exoplanet Archive[1]. After removing incomplete data, such as missing names or duplicates, the dataset was reduced down to about 6,000 planets. The model considered factors like planet mass, planet radius, equilibrium temperature, stellar flux, and orbital details, along with host star traits such as spectral type, mass, luminosity, and effective temperature. To refine the analysis further, five key factors were chosen out of the ones listed: planet mass, planet radius, equilibrium temperature, stellar flux, and tidal locking. Each planet received a habitability score from 0 to 10, with Earth serving as the benchmark at 10. Out of the 6,000 planets, only 38 met the criteria and were classified as rocky with potential for habitability, and around 11 of these candidates overlapped in other exoplanet catalogs, such as PHL[2]. Most of these 38 planets scored in the medium habitability range, indicating that while they may have some characteristics that are similar to Earths, they fall short of being exactly Earth-like. Although the model does not account for atmospheric or surface conditions, it provides a model that may guide future research in the ongoing search for potentially habitable worlds.

Keywords and phrase: exoplanets, habitable, NASA dataset, analysis, future studies

Introduction

The rapid discovery of thousands of exoplanets over the past decades has sparked one of the biggest questions in astrobiology and science in general[3]: Which of the many discovered worlds should be prioritized for follow-up and which ones can host life like our own Earth? Simple rules such as the conventional habitable zone are useful but incomplete, because habitability depends on many planetary and stellar factors rather than a single check mark[4],[5],[6],[7]. As a result there is a clear need for models that can filter large datasets and rank targets according to measurable properties[8].

To address this need, a scoring system was applied to the NASA Exoplanet Archive[1]. The process consisted of three main steps. First, cleaning and filtering the raw data to create a clean sample. Second, giving planets a weighted habitability score based on key planetary and stellar parameters. Finally, identifying the planets that were most similar to Earth according to these parameters. The analysis focused on commonly used parameters, such as planet mass and radius, equilibrium temperature, stellar flux, and tidal-locking potential with additional filters being added to help remove planets that were clearly non-rocky[9]. Although the model took a cautious approach, there were still many limitations, some of the major ones are noted up front: Atmospheric and surface compositions are not available in the dataset and therefore are not included[10]. Observability is also not incorporated into the model and is classified as future work, which complicates follow-up studies, as some promising planets may be too dim or distant to be effectively observed with current telescopes. Another major limitation is that the scoring is intentionally Earth-centric, meaning it favors habitability as we know it and will not be able to capture exotic life possibilities[11]. Despite these limitations, the model offers a framework that can be adjusted to guide follow-up studies on the most promising targets.

Methods

This study looks at potentially habitable exoplanets from the NASA Exoplanet Archive[1] and ranks them using a multi-factor scoring system with filtering. The approach aims to include as many planets as possible while keeping the results scientifically realistic. The main focus was on Earth-like habitability while also acknowledging that planets can be very different from one another, including Earth.

Data Acquisition

The analysis was conducted with the data used from the NASA Exoplanet Archive[1]. The dataset initially contained around 38,000 entries for exoplanets, including duplicates. The first step in cleaning the data was to make sure all relevant columns were in numeric format[12] [13] [14] with any non-numeric entries being replaced with NaN so that calculations could be performed

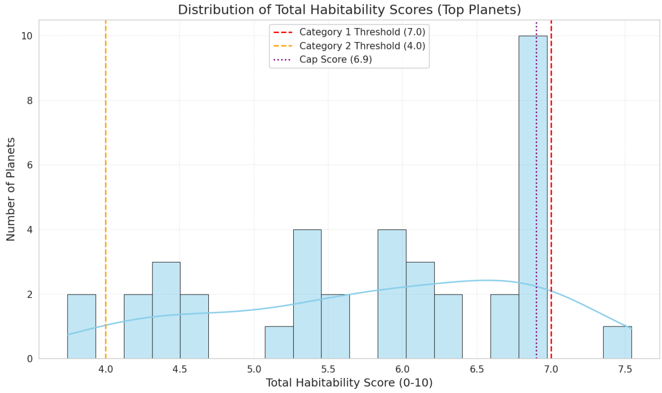

Fig. 1 Distribution of Habitability Scores and Categorization.

correctly[15]. To completely focus on rocky exoplanets, a filter was applied, removing planets with radius over 10 RŁ, which were classified as gas giants. After the filtering and removing entries with insufficient data like missing planet name or no parameters, and duplicates, around 6,000 exoplanet entries remained for further analysis.

Derivation of Parameters

The next step was handling the missing data for parameters needed for assessing habitability. When direct measurements were not available, usual astronomical laws were used to estimate them:

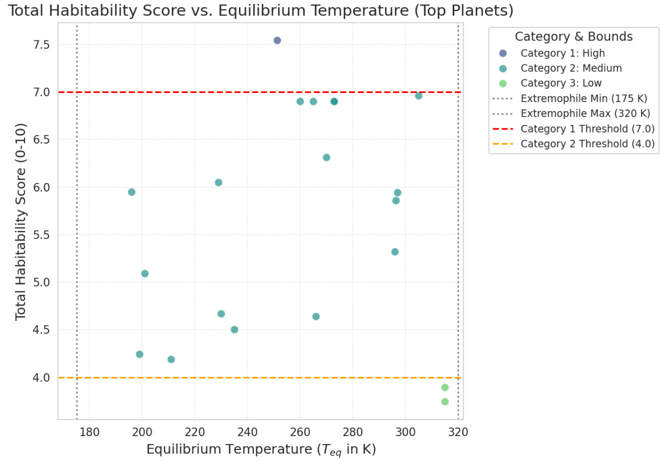

Fig. 2 Relationships Between Key Parameters and Total Habitability Score

- Stellar Luminosity (L): If a stars luminosity (brightness) was missing in the dataset, it was estimated using the Stefan-Boltzmann law, which says that a stars luminosity depends on its radius and surface temperature[16]. Where L = stars luminosity, R = radius of the star, σ = Stefan-Boltzmann constant, and T = effective surface temperature of the star.
  Formula: $L = 4\pi R^2 \sigma T^4$
- Semi-Major Axis (a): For planets with a missing semi-major axis (pl_orbsmax), Kepler's Third Law was used, and the semi-major axis was found using orbital period (in seconds, P) stellar mass (in kilograms, M), where G is the gravitational constant, and reported in AU[17].
  Formula: $a^3 = \dfrac{GMP^2}{4\pi^2}$ The orbital period (pl_orbper) was converted from days to seconds, and stellar mass (st_mass) from solar masses to kilograms.
- Incident Stellar Flux (S): If incident stellar flux (pl_insol) was missing, it was calculated with the help of the derived stellar luminosity and semi-major axis, expressed in multiples of Earth's solar constant ($S_\oplus = 1361\ \mathrm{W/m^2}$)[18].
  Formula: $S = \dfrac{L}{4\pi a^2 S_\oplus}$

Assessment of Tidal Locking

Tidal locking can significantly impact habitability for planets[19 20]. Planets orbiting M-dwarf stars (identified as spectral type M) or stellar effective temperatures below 3700 K were assumed to be tidally locked. Not every planet orbiting an M-dwarf may be tidally locked, but this assumption gives a way to account for the higher chance of tidal locking[21].

Habitability Scoring Model

A scoring model was designed to evaluate the potential habitability of exoplanets on a scale of 0-10. It uses five key parameters, each one contributing to the total score using adaptive weighting. This accounts for missing data, ensuring that planets with incomplete information receive scores that fairly reflect what is known.

Parameter Selection and Individual Scoring

The five key parameters selection was based off of their relevance to the presence of liquid water and the potential to host life, these five include[22]

- Planetary Features:
  - Planet Radius (pl_rade, $R_\oplus$): Planet radius is important for distinguishing rocky planets from gas giants. The score (S_radius) was maximized for Earth-like radii (1.0 $R_\oplus$) and decreased for deviations, reaching zero at 0.5 $R_\oplus$ and 1.8 $R_\oplus$. Planets that exceeded the threshold max of 1.8 $R_\oplus$ were considered non-rocky and filtered out.

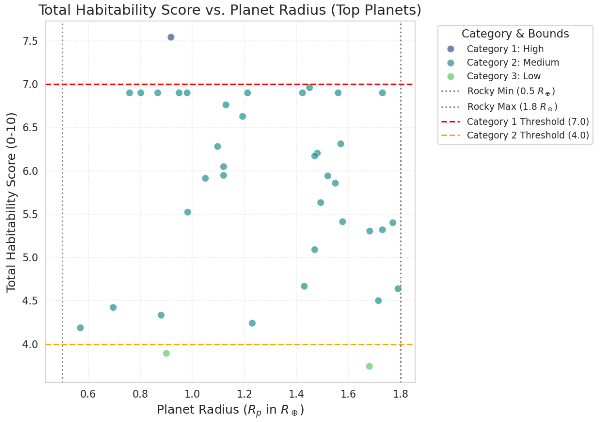

Fig. 3 Relationship with planet radius (pl_rade) and the total score.

- ○ Planet Mass (pl_masse, $M_\oplus$): A planets mass affects its ability to have an atmosphere and support geological activity. The mass score (S_mass) was highest for an Earth-like mass (1 $M_\oplus$) and decreased for values further from this benchmark, dropping to zero at 0.1 $M_\oplus$ and 10 $M_\oplus$[23]. Planets exceeding 10 $M_\oplus$ were also classified as gas giants.
- ○ Equilibrium Temperature (pl_eqt, Kelvin/K). Temperature relates to the potential for liquid water. The score (S_temperature) was maximum within the preferred range of 273 K to 303 K. Half score was given for temperatures within the range of 175 K272 K and 304 K320 K in which some life forms can still survive[24][25]. It should be noted that equilibrium temperature does not account for atmospheric effects such as greenhouse gases, so the actual surface temperature may be different. Despite this, equilibrium temperature provides a useful estimate for comparing habitability potential[26].

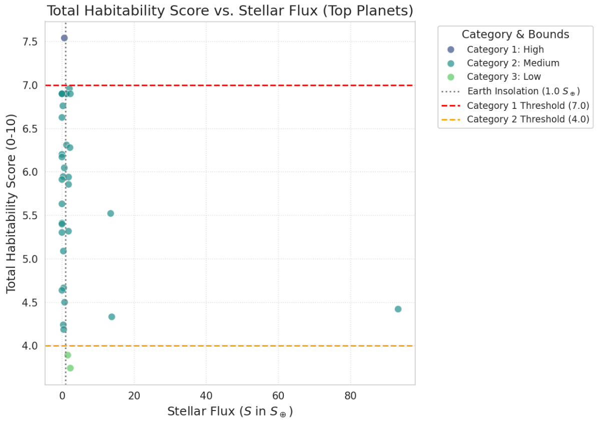

Fig. 4 Relationship between the total score and pl_insol (Stellar Flux).

- Stellar/System Features
  - ○ Stellar Flux (pl_insol, multiples of Earth's solar constant, $S_\oplus$): Stellar Flux determines how much energy a planet receives from its star. The score (S_flux) was maximized at 1.0 $S_\oplus$ and was gradually decreased for values further from the benchmark.
  - ○ Tidal Locking (is_tidally_locked): Tidal locking reduces habitability potential due to extreme temperature differences between two sides of a planet[19]. The score (S_tidal) was maximum for non-tidally locked planets and 0.0 for tidally locked ones.

Each parameter was scaled so that the best value gets a score of 1 and the worst gets a score of 0, with everything in between being assigned proportionally. If a planet did not have a value for a parameter and could not be calculated, that score was left blank, and the final habitability score was adjusted based only on the available data.

Adaptive Weighting and Score Calculation:

The total score for each planet was calculated using adaptive weighting. Each of the five parameters were assigned a weight based on its importance for habitability: S_radius (20%), S_mass (20%), S_flux (18%), S_tidal (12%), and S_temperature (30%). The total habitability score (Total_Score) ranges from 0 to 10 and was calculated by multiplying each parameters score by its weight and then adding them. If a planet was missing data for specific parameters and the missing parameter could not be calculated using an operation, only the available ones were used, and due to adaptive weighting, the weights are adjusted so the final score still stays on the 0–10 scale.

$$\text{Total\_Score} = 10 \times \frac{\sum(S_i W_i) \text{ for } i = 1 \text{ to } N}{\sum W_i \text{ for } i = 1 \text{ to } N}$$

Where S_i is the individual score for parameter i, W_i is its assigned weight, and N is the number of available parameters.

Disqualification and Capping Gates

To keep the results accurate and to filter out planets that did not make sense scientifically, a system of gates and caps was used. This led to some candidates being disqualified, while others had their scores capped.

Initial Disqualification Filters

- Gas Giants: Planets that were identified as gas giants were removed from further analysis. Any planet with a radius larger than $1.8R_\oplus$ or a mass greater than $10M_\oplus$ was automatically assigned a total score of 0.0. The reason for this being that gas giants lack solid surfaces and cannot

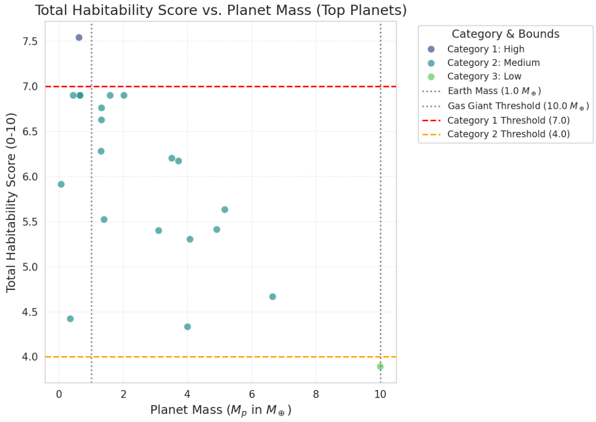

Fig. 5 Total score against planet mass (pl_masse).

support life as we know it. If the available data was insufficient to determine whether a planet fit this category, its gas giant status (gas_giant_status_display) was recorded as "Unknown" and not filtered out, giving it the benefit of the doubt.

- Extreme Equilibrium Temperature: Planets with a measured equilibrium temperature (pl_eqt) falling outside the range of 175 K to 320 K which is relatively extremophile friendly received a total score of 0[24]. This makes sure that only planets with the potential for liquid water are considered.

Data Completeness Gate for Medium Category Eligibility

To prevent planets with minimal data from achieving a High or a "Medium" habitability status easily, a data completeness filter was implemented. A planet needs to have at least 3 non-missing valueseither measured or givenfor its core habitability parameters (pl_rade, pl_masse, pl_eqt, pl_insol) to be eligible for any score above 1.0. If a planet fails this test, and is not already disqualified to 0.0, its total score is set to 1.0, placing it in Category 3: Low.

Habitability Score Capping

- General Data Sparsity Cap: Even if a planet has enough core data (≥ 3 parameters), if the sum of weights for its measured core features (pl_rade, pl_masse, pl_eqt, pl_insol) falls below a threshold of 0.55, its total score is capped at 6.9 placing it in the Medium category, just shy of Category 1 to make sure only the top candidates are selected for the top category.
- ESI Consistency and Weighting Justification: The Earth Similarity Index (ESI) was calculated separately and used as a consistency check after scoring. ESI is useful as it combines key planetary traits such as radius, density (from mass), and stellar flux or surface temperature into a value out of 1.0 that shows how physically similar a planet is to Earth. Planets with an ESI below 0.40 were not eligible for Category 1 and were capped at a maximum score of 6.9. ESI was not used in the main scoring formula to make sure circular reasoning did not occur.

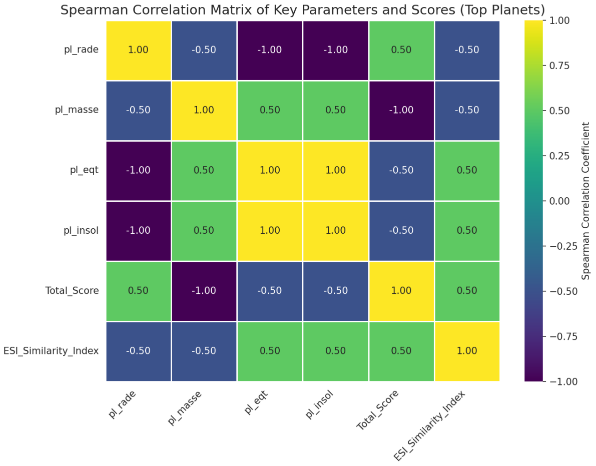

Fig. 6 Planetary parameters relate to each other and to the habitability score.

Formula[27]:

$$\mathrm{ESI} = 1 - \sqrt{\frac{1}{2}\left[\left(\frac{S_p + S_\oplus}{S_p - S_\oplus}\right)^2 + \left(\frac{R_p + R_\oplus}{R_p - R_\oplus}\right)^2\right]}$$

Where S_p is the planet's stellar flux and R_p is its radius, with Earth's values ($S_\oplus, R_\oplus$) used for comparison. ESI was calculated whenever the necessary inputs (radius/mass for derivation, and stellar flux) were available or calculatable.

- To keep consistency, two flags were made `is_capped_by_esi_gate` and `flag_low_ESI_high_score_inconsistency`. These highlight planets where the scoring model suggests high habitability, but the ESI metric does not agree, capping the planets score at 6.9
- Hard Physical Gates for Category 1 Eligibility: For a planet to receive a total score of 7.0 or higher, it must meet all of the conditions listed below:
  - Planet radius (pl_rade) needs to be measured and be within 0.5 and 1.8 $R_\oplus$.
  - Planet mass (pl_masse) must be measured and be within 0.1 $M_\oplus$ and 10.0 $M_\oplus$.
  - Equilibrium temperature (pl_eqt) has to be measured and be within 175 and 320 K[24].

  - Stellar flux (pl_insol) must be measured relative to Earth.
  - ESI (ESI_Similarity_Index) needs to be measured and be over a 0.40[27].

If a planet's calculated total score would otherwise be over a 7.0 but failed to hit any of these conditions, its score was capped at 6.9, demoting it to Category 2: Medium. This makes sure that only the most promising planets with measured parameters are placed in the High" category.

Habitability Categorization

Based on the total score, planets were assigned to one of three habitability potential categories:

- Category 1: High (≥ 7.0)
- Category 2: Medium ($4.0 \leq \text{Score} < 7.0$)
- Category 3: Low (< 4.0)

Selection of Top Exoplanets

The final list of the "Top Habitable Exoplanets", consisted of 38 planets and was determined by sorting the dataset based on the following:

1. Total score (Total_Score) (Descending): Prioritizing planets with higher calculated habitability potential.
2. Data completeness (data_completeness_count) (Descending): As a second tie-breaker, prioritizing planets that had more of the five key parameters known (radius, mass, equilibrium temperature, stellar flux, and tidal locking status).
3. ESI (ESI_Similarity_Index) (Descending): As a third tie-breaker, prioritizing planets with higher Earth Similarity Index values when total score and data completeness were the same.

Statistical Analysis and Model Validation

For future testing, the dataset will be split into two parts: 70% for training the model and 30% for testing it, using a fixed random seed so the results are consistent. To check accuracy and limit bias, cross-validation methods (such as k-fold) will also be used to make sure the model performs well on new data.

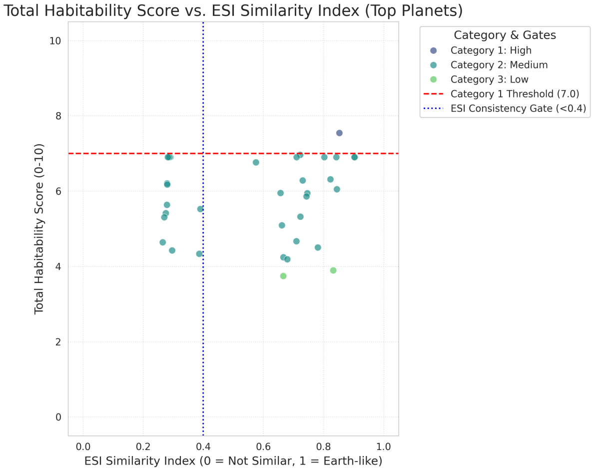

Fig. 7 ESI_Similarity_Index_served

Results

This section shows the results of applying the habitability scoring model to the data from the NASA Exoplanet Archive (1). It covers what the dataset looks like after processing, how the habitability scores are distributed, how key parameters relate to one another, and which planets ranked highest as the most promising candidates. There were 38 main candidates after the filtering and capping.

Distribution of Habitability Scores and Categorization

Score Distribution: The habitability scoring model assigned total scores from 0 to 10 for the analyzed exoplanets. As shown in Figure 1, the distribution of scores strongly leaned toward Category 2. Many planets were capped, shown by the dotted purple line, suggesting few more planets may be eligible for Category 1 as more data becomes available. The dashed red line highlights the only planet that reached Category 1. These results show how strictly the disqualification and score-capping rules shaped the outcomes, only planets meeting the criteria mentioned in the Methods section were able to achieve the higher habitability scores.

Relationships Between Key Parameters and Total Habitability Score

The way total scores correspond to the individual key parameters highlights which factors influence habitability in the model the most.

Temperature: Figure 2 illustrates the relationship between the total score (Total_Score) and its equilibrium temperature (pl_eqt). Planets with total score over a 4 are concentrated within the 175 K to 320 K range, with the highest scores generally found in the 250 K to 305 K window. The figure also illustrates that only a half of the 38 planets, since these were the only ones who had their equilibrium temperature available[24].

Planet Radius: Figure 3 shows the relationship with planet radius (pl_rade) and the total score. It suggests that capped planets appear across almost the entire 0.7–1.7 R⊕ range. This pattern highlights how the size shaped the selection of rocky planet candidates.

Stellar Flux: Figure 4 displays the relationship between the total score and pl_insol (Stellar Flux). Optimal scores are concentrated around 1.0S⊕, with scores decreasing for both lower and higher incident flux.

Planet Mass: Figure 5 presents the total score against planet mass (pl_masse). High scores are concentrated around 1.0 M⊕, with a decrease as it goes further from this benchmark, particularly when planet mass begins to enlarge. Planet mass plays a very important role in the model, since it directly affects both atmosphere retention and geological activity.

Spearman's rank correlation: Figure 6 was used to explore how planetary parameters relate to each other and to the habitability score. The total score showed a moderate positive correlation with radius ($+0.50$) but a strong negative one with mass (-1.00), suggesting that in this dataset, larger but lighter planets tended to score higher. Both equilibrium temperature and stellar flux were moderately negatively correlated with the total score (-0.50), while the two were perfectly correlated with each other, as expected. Radius and mass also showed opposite trends with irradiation, illustrating strong interdependencies. The ESI correlated moderately with the total score ($+0.50$) but weighted properties differently, being positively tied to flux and temperature while negatively tied to radius and mass.

ESI Similarity index: The ESI_Similarity_Index served as an external check to validate the models results[27]. A scatter plot of total score vs. ESI (Figure 7) shows how this consistency gate works in practice. Planets that earned a score of 7.0 or higher but had an ESI below 0.40 (dotted blue line) were capped at 6.9, moving them into Category 2: Medium. This gate helps verify that Category 1 candidates are the most credible.

The "top" Habitable Exoplanets

The final "top" list of potentially habitable exoplanets was sorted by: first, total score, then by data completeness, and finally by Earth Similarity Index (ESI). This way, high-ranked planets had more evidence supporting them. The list only included the planets that had a Total Score of 3.0 or better, reducing the list to 38. Of those 38, approximately 11 overlapped with the PHL catalog (August 2025): TRAPPIST-1 e, Kepler-438 b, TOI-700 e, Kepler-442 b, Kepler-62 e, Kepler-1229 b, Kepler-296 e, Kepler-296 f, Kepler-1649 b, Gliese 12 b, and LHS 1140 b[2]. This shows how even when catalogs agree on some planets, their actual habitability has yet to be determined.

TRAPPIST-1 e was the highest-ranking planet with a total score of 7.54 and an ESI of 0.85 placing it as the only planet in Category 1: High[28]. Its entire data set (all 5/5 available), either by derivation of parameters or being available from the start, supports its potential as a candidate for further study. This is important because there are still many uncertainties remaining, like atmospheric composition. Most of the other planets in the Top 38 ranked in Category 2: Medium, with a small amount in Category 3, as most of the Category 3 were already filtered out due to safeguards. There were also a few planets restricted by physical or ESI gates, managing to keep them from being rated too high. This shows the rarity of top tier Earth-like candidates.

Discussion

Out of roughly 38,000 known exoplanets, only a small fraction made it through the models filtering and scoring process, leaving 38 candidates that stood out as potentially habitable. This shows how rare Earth-like planets are in the current exoplanet catalogs such as NASAs, according to the model. The disqualification and score caps helped remove planets that did not meet the habitability criteria, making the final list more reliable. While there is still a lot of uncertainty about these planets, this set of planets provides a useful starting point for future studies.

Interpretation of Key Findings

The distribution of habitability scores mostly skewed toward medium and lower values, illustrating how conservative the model is. Many exoplanets have some traits that could support habitability, but a very small number meet all the key criteriasize, mass, temperature, and stellar fluxwhile also having enough data. Most planets were categorized as Category 2 (Medium) or Category 3 (Low), which indicates the impact of the disqualification and capping filters, such as automatically scoring gas giants or very hot/cold planets as 0, or capping planets with missing data, so that the model will not overestimate habitability.

Adaptive weighting was also important because it offset parameters that could not be calculated, allowing planets to keep higher habitability scores despite missing data However, the data sparsity cap worked as another filter, filtering planets with extensive data gaps from reaching Category 1 even when the available numbers were favorable. Along with that, the hard physical gates and ESI consistency check worked as one more filter, so planets without enough data could not end up in the highest category.

The fact that the total score and the ESI are moderately positively correlated boosts confidence that the scoring model behaves reasonably accurately. In the end, the final list of 38 exoplanets, led by TRAPPIST-1 e, features planets that not only have favorable physical properties but also have mostly complete data, making them stand out as strong candidates.

Limitations

Even though this model takes a cautious approach, there are still many important limitations that come from both the available data and the way habitability is defined.

- Earth-Centric Bias: The model is Earth-life-centric, and checks for conditions that would allow for liquid water and rocky surface to exist. While there was an extended temperature range to account for extremophiles, it was to an extent. The model does not attempt to account for more exotic habitability that might exist under very different conditions. This choice was made intentionally as it makes the definition of habitability much simpler, but it restricts the results to life ”as we know it.”
- Lack of sure conclusions: While 38 planets were identified as promising candidates based on their parameters, this does not mean they are guaranteed to be habitable. Many of these planets lack complete data, and even then, favorable characteristics might not fully translate to conditions that certainly support life. These planets should instead be seen as promising leads for further study rather than confirmed habitable worlds.
- Database and Observational Biases: The NASA Exoplanet Archive[1] by itself is not a perfect sample of exoplanets in the galaxy. The data is biased towards large planets with shorter periods around smaller and cooler stars because of the methods used to discover planets (mainly transits from Kepler and TESS)[29 30 31]. This led to the results being influenced by these biases and do not reflect the full diversity of planetary systems.
- Missing Parameters and Static Evaluation: For most planets, direct measurements for important properties are lacking, such as, and especially, atmospheres. The model relies on parameters like equilibrium temperature and stellar flux, but they become unreliable after taking atmospheric effects into account. Besides that, the model’s scoring system only shows one ”snapshot” of each planet and does not consider how habitability can change over time due to stellar or planetary evolution.
- Telescope Observability: Another limitation is that observability was not included in the score. Planets may be promising in the model but too distant or orbit stars that are too faint to follow-up with telescopes like JWST or the ELT. As a result, this will lead to the ”top list” including planets that are scientifically interesting but not currently practical to study more in detail.
- Statistical Significance Assessment: While Spearman rank correlations were implemented to assess relationships between parameters and habitability scores, p-values were not calculated due to limitations in the current implementation. This restricts the ability to fully determine statistical strength for these correlations.
- No Advanced Statistical Analysis: Finally, the approach was rule-based and did not include more advanced methods such as PCA, clustering, or regression that might have uncovered hidden patterns or could have added additional validation to the scores, but those methods were outside the scope of this first version.

Future Work

There are several ways in which the model could be improved going forward:

- Advanced Statistical Modeling: Applying PCA, clustering, or regression models might reveal natural clusters of planets and refine habitability scores more.
- Incorporation of p-values: Incorporation of p-values calculation would strengthen the analysis and provide increased accuracy.
- Atmospheric Data Integration: As atmospheric data becomes available, building models that include atmospheric composition, greenhouse effects, and potential biosignatures into the total score would increase accuracy.
- Refined Tidal Locking Models: More complex tidal locking models that take into account eccentricity and internal composition would be useful for tidally locked planets, especially M-dwarf planets. This could lead to more reliable surface condition determinations.
- Extended Habitability Factors: Adding more habitability-determining factors such as climate stability, tectonic activity, and water availability would also make the scores much more reliable.
- Optimizing for Observability: Lastly, including observability as a scoring factor would allow the model to be aligned with realistic follow-up candidates, so the ”top” worlds would also be realistic targets for future telescopes.

Conclusion

This study built and tested a scoring model to filter through more than 38,000 entries of exoplanets in the NASA Exoplanet Archive[1] and created a list of which of these worlds would be the most viable candidates to support life. The study used filters that eliminated obvious non-contenders like gas giants, planets with extremely high or extremely low temperatures, and cross-checking results using the Earth Similarity Index, the model narrowed the list down to just 38 planets which came out to be promising candidates.

The results show that truly Earth-like planets are very rare in current data. As expected, most of the 38 planets were placed in either categories medium or low. In the future, the model could be improved with new data as it comes in, especially from missions like the James Webb Space Telescope and TESS[32] Adding factors such as atmosphere, volcanic activity, etc. could contribute to a more complete understanding of what makes a planet potentially habitable. Over time, the approach could shift from just spotting Earth-like worlds to exploring a wider range of environments where life might exist.

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