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Evaluating Terrestrial Exoplanet Habitability Using an Interior Earth Similarity Index Model

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Abstract: With over 5000 confirmed exoplanets, astronomers need a more simple and efficient way to evaluate the habitability of each planet. The goal of this research project is using data from the NASA Exoplanet Archive and the ESI index (earth similarity index) to rank rock samples- a sample of terrestrial (rocky) prefiltered to be located within their star's habitable zone- planets based on two main criteria : planetary size and distance from their host star . Our results successfully rank some high probability worlds and identify top tier candidates such as Kepler 1649c and Ross 128 b at the apex of similarity to earth. To minimize assumptions and to account for the majority of planetary surfaces, this project isolates interior ESI, evaluating candidates strictly on physical parameters: planetary size, bulk, and density. Ultimately this provides a baseline for future atmospheric characterization.

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I. INTRODUCTION

The field of astrobiology provides ground for the intersection of the fields of astronomy and biology ; it looks at the biological origins of the universe, studies the future of the species in space and researches possible life outside of earth.

The rapid expansion of exoplanetary (planets outside of our solar system) discovery due to telescopes like Kepler and James Webb has led to it becoming more and more critical to find a way to distinguish habitable and uninhabitable planets among their midst of the thousands already discovered.

It is vital to turn to exoplanets to further technological advancements which is important to improve ourselves as a species further. To allow us to develop space and learn more about it is crucial to developing a further understanding of our universe.

It is also essential to learn more about exoplanets as human actions by burning greenhouse gasses will slowly raise the earth's temperature making it an uninhabitable environment for humans to live in . This is why the finding of hospitable environments on exoplanets is one of the most crucial scientific quests of our time, not only for technological discoveries, but for the future survival of humans as a race.

This project's main goal is to use the NASA Exoplanet archive (*NASA Exoplanet Archive*, n.d.) to identify the most likely candidates from the presently discovered planets. This will be done through ESI in two main criteria :

- Planetary size - this is important that they have enough mass to have a strong enough gravitational pull to support water, even in frozen form, to long enough to support life astronomers use the percentage of earth's mass as an index of the size the smallest planet must be at least 0.268 of earth's mass. Planetary size
- Planetary density and bulk - bulk density (the mass considering volume) is critical to determining a planets habitability as it reveals the planet's broad internal composition allowing astronomers to distinguish between gaseous worlds, water dominated worlds, and iron rich planets. This is critical information for choosing a suitable habitable planet.

To address this we will use ESI to compare the planets in the NASA exoplanet dataset in the two key metrics I have provided : Planet mass/ size, Planetary bulk density. This will provide us with a key metrics to address the question in this paper, identifying and ranking the top five discovered exoplanets most likely to support life outside of earth, and which is likely to be able to support humans on the surface.

II. METHOD & DATA ANALYSIS

The data set for this investigation was compiled from using the confirmed exoplanets from the NASA exoplanet archive. Out of more than 5,000 confirmed entries a multistage filtering algorithm was used to isolate rocky terrestrial planets, the planets with the most chance of supporting surface liquid water, a multi stage filter was applied in order to find the planets most likely to support life.

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To narrow down the dataset, planets were evaluated against two mandatory physical parameters :

- Planetary Mass - The planets in my study will be restricted to a lower mass bound of 0.268 M⊕ (where M⊕ is earths mass). This ensures that the gravitational pull is strong enough to retain a stable atmosphere
- Planetary bulk and density - The planets in this project must have a lower planetary bulk bound of 3.8 g/cm³ and the highest bound of 6.0 g/cm, this ensures a planet is inhabitable, and falls into the category of rocky and terrestrial planets (Rogers, 2015)

To evaluate and rank the remaining candidates we will implement the ESI index (earth similarity index) (Schulze-Makuch et al., 2011)to find planets most likely to sustain life like our own. Calculating ESI allows a simple way to measure a planet's similarity to our own The formula used to calculate ESI is :

$$ESI_x = \left(1 - \left|\frac{x - x_0}{x + x_0}\right|\right)^{w_x} \quad (1)$$

Where:

x- is the exoplanets property (e.g : radius, temperature, density)

x_0- is the earth's baseline for that same property

w_x- the weighting exponent, which determines how sensitive the index is to deviations

By calculating the individual ESI of the two main criteria, it allows for an overall geometric ESI score to be calculated using all of the components to provide a more reliable outcome :

$$ESI_{general} = \prod_{i=1}^{n} (ESI_i)^{\frac{1}{n}} \quad (2)$$

Here we multiply our results together for n times, in this study n=2 this calculates the avarge . Planets scoring closest to 1.00 have the highest chance of supporting life and sustaining liquid surface water. This shows planets closest to earth parameters, meaning since earth supports life, is likely to hold life as well.

III. RESULTS & TOP 5 CANDIDATES

To answer the research question, a sample of 30 terrestrial planets was extracted from the NASA exoplanets archive by applying initial boundaries for mass ($M \geq 0.268$ ⊕), orbital distance, and EST (273 K- 343 K0. Using spreadsheet modeling, the two step ESI formula was applied to calculate the physical similarities to the earth's baseline (1.00).

Table 1 ESI Formula

2	GJ 3323	1	2 Radial Velocity	2017 La Silla Observa	0	5.3636	0.03282	1.23	0.109	2.02	0.0063356 Mo/ri		0.23	2.58	290.06	0 M4	3159	0.119	0.164	-0.27 [Fe/H]	05h01m56.85s	75.4668024 -00d50m54.65s	-6.9481133	5.37484	12.57	6.736	10.6467	0.917801013
3	Ross 128	1	1 Radial Velocity	2017 La Silla Observa	0	1.3658	0.0496	1.11	0.0998	1.4	0.00440487 Mo/ri		0.116	1.38	301	0 M4	3192	0.1967	0.168	-0.02 [M/H]	11h47m44.02s	176.9076135 +00d47m57.44s	0.7982899	3.37464	11.12	5.654	9.58067	0.943434094
4	TOI-700	1	4 Transit	2023 Transiting Exopl	0	27.80978	0.134	0.953	0.06932111	0.818	0.00257 M-R relationship		0.059	1.27	272.9	0 M2.5 V	3459	0.421	0.415	-0.07 [Fe/H]	4.809 0h12m22.97s	97.0957165 -65d24m43.01s	-65.5786149	31.1265	13.151	8.634	12.0665	0.853505727
5	TOI-715	1	1 Transit	2023 Transiting Exopl	0	19.288004	0.083	1.55	0.13828198	3.02	0.00351 M-R relationship			0.67	234	0 M4	3075	0.24	0.225	-0.25 [Fe/H]	5.07h35m24.56s	113.8523276 -7d34m36.67s	-73.5774089	42.4048	16.683	10.917	14.894	0.913528687
6	Kepler-438	1	1 Transit	2015 Kepler	0	35.23319	0.166	1.12	0.1	1.46	0.00459 M-R relationship		0.03	1.4	288	0	3748	0.52	0.544	0.16 [Fe/H]	4.74 19h49m34.93s	287.8457236 +44d57m03.85s	41.8518866	196.9428716	15.134	11.199	14.4952	0.877339349
7	a Tauri Sta	1	3 Radial Velocity	2019 Calar Alto Obser	0	4.9834	0.0259	1.05	0.0937	1.16	0.00364977 Mo/ri		0.03	1.08	277	0 M7.0 V	3034	0.12	0.097	-0.11 [Fe/H]	5.19 02h53m04.59s	43.2691449 +16d51m53.65s	16.9649824	3.93079	15.13	7.585	12.2746	0.870711026
8	GJ 1061	1	3 Radial Velocity	2020 La Silla Observa	0	13.006	0.054	1.16	0.104	1.67	0.00525441 Mass		0.04	0.6	242.03	0 M5.5 V	2953	0.156	0.12	-0.06 [Fe/H]	5.19856 03h36m00.78s	54.0032486 -44d03m51.52s	-44.5143104	3.67278	12.7	6.61	10.9889	0.823643274
9	Kepler-1649	1	2 Transit	2017 Kepler	0	9.690099	0.0514	1.017	0.09073096	1.03	0.00325 M-R relationship		0	2.209	307	0	3240	0.2317	0.1977	-0.15 [M/H]	5.004 19h30m00.71s	292.5029676 +51d06m47.98s	41.8299933	92.1913	17.95	12.589	16.2682	0.815775877
10	Kepler-1229	1	1 Transit	2016 Kepler	0	86.828699	0.3008	1.4	0.12499653	2.54	0.006 M-R relationship		0	0.524	212	0	3784	0.51	0.54	-0.06 [Fe/H]	4.75 19h49m58.84s	297.4968347 +46d59m48.04s	46.8966782	269.482	16.124	12.074	15.5104	0.965104187
11	GJ 1061	1	3 Radial Velocity	2020 La Silla Observa	0	8.6821	0.0342	1.19	0.106	1.81	0.0056949 Mass		0.02	1.4	304.12	0 M5.5 V	2953	0.156	0.12	-0.06 [Fe/H]	5.19856 03h36m00.78s	54.0032486 -44d03m51.52s	-44.5143104	3.67278	12.7	6.61	10.9889	0.778155273
12	TRAPPIST-1	1	7 Transit	2017 Multiple Observe	0	9.20754	0.03849	1.045	0.09022892	1.039	0.00326906 Mass		0.01007	0.373	217.7	1 M8.0 V	2566	0.1192	0.0898	0.052 [Fe/H]	5.2396 23h09m30.33s	346.6263019 -05d02m36.46s	-5.0434618	12.42988681	17.02	10.296	15.6451	0.940326972
13	GJ 3378	1	1 Radial Velocity	2026 Mauna Kea Obs	0	21.45	0.09673	1.32	0.118	2.3	0.00723981 Mo/ri		0	0.91	272	0 M4 V	3340	0.275	0.262	-0.09 [Fe/H]	4.97 09h01m10.83s	90.2951302 +09d35m35.49s	59.5931917	7.73274	12.37	6.659	10.4084	0.887199892
14	Kepler-1652	1	1 Transit	2017 Kepler	0	38.19722	0.1654	1.0	0.14274244	3.19	0.01 M-R relationship		0	0.81	268	0	3638	0.302	0.404	-0.3 [Fe/H]	4.678 19h37m27.85s	294.3660313 +49d54m54.08s	49.9155219	252	16.86	12.635	16.0023	0.826193748
15	GJ 273	1	2 Radial Velocity	2017 La Silla Observa	0	10.6498	0.091101	1.51	0.135	2.89	0.00909291 Mo/ri		0.1	1.06	292.47	0 M3.5	3382	0.293	0.29	0.09 [Fe/H]	4.90868 07h27m24.50s	111.652091 +05d13m32.91s	5.229807	5.921535	9.94	4.857		0.686547918
16	GJ 1002	1	2 Radial Velocity	2022 Multiple Observe	0	21.202	0.0738	1.1	0.098	1.56	0.00427804 Mo/ri			0.267	181.7	0 M5.5 V	3024	0.137	0.12	-0.25 [Fe/H]	5.1 00h06m42.35s	1.6764641 -07d02m46.38s	-7.5462123	4.84667	13.76	7.439	11.7804	0.764219814
17	a Tauri Sta	1	3 Radial Velocity	2019 Calar Alto Obser	0	11.416	0.0455	1.02	0.0912	1.05	0.00330367 Mo/ri		0.04	0.35	269	0 M7.0 V	3034	0.12	0.097	-0.11 [Fe/H]	5.19 02h53m04.59s	43.2691449 +16d51m53.65s	16.9649824	3.93079	15.13	7.585	12.2746	0.869523421
18	TRAPPIST-1	1	7 Transit	2017 Multiple Observe	0	6.101013	0.02925	0.92	0.08207704	0.692	0.00217729 Mass		0.0051	0.646	249.7	1 M8.0 V	2566	0.1192	0.0898	0.052 [Fe/H]	5.2396 23h09m30.33s	346.6263019 -05d02m36.46s	-5.0434618	12.42988681	17.02	10.296	15.6451	0.804643102
19	Kepler-62	1	5 Transit	2013 Kepler	0	267.291	0.718	1.41	0.126	35	0.11 Mass		0	0.5	208	0 K2 V	4925	0.64	0.69	-0.37 [Fe/H]	4.68 19h32m51.01s	283.2129621 +45d20m58.92s	45.3499592	330.874	13.955	11.659	13.7197	0.931998693
20	Kepler-1649	1	2 Transit	2020 Kepler	0	19.53527	0.0649	1.06	0.09458697	1.2	0.00377 M-R relationship		0	0.75	234	0	3240	0.2317	0.1977	-0.15 [M/H]	5.004 19h30m00.71s	292.5029676 +51d06m47.98s	41.8299933	92.1913	17.95	12.589	16.2682	0.950119825
21	TOI-700	1	4 Transit	2020 Transiting Exopl	0	37.42396	0.1633	1.073	0.09573591	1.25	0.00394 M-R relationship		0.042	0.85	268.8	0 M2.5 V	3459	0.421	0.415	-0.07 [Fe/H]	4.809 0h12m22.97s	97.0957165 -65d24m43.01s	-65.5786149	31.1265	13.151	8.634	12.0665	0.783449801
22	GJ 1132	1	2 Radial Velocity	2018 La Silla Observa	0	8.929	0.0476	1.62	0.135	2.91	0.00915588 Mo/ri		0.19	2.1053	300	0 M4.5 V	3090	0.226	0.198	-0.16 [Fe/H]	5.02 10h14m50.18s	153.7090696 -47d01m17.77s	-47.1545358	12.613	13.68	8.322	12.138	0.794479737
23	Kepler-1126	1	2 Transit	2023 Kepler	0	199.68878	0.6193	1.45	0.12836056	2.7	0.00849 M-R relationship		0	2.08	305	0	5878	0.921	0.794	-0.4 [Fe/H]	4.409 19h02m40.07s	285.6919555 +50d01m21.84s	45.6883983	635.736	14.221	12.534	14.0207	0.862857185
24	Proxima Cen	3	2 Radial Velocity	2016 European South	0	11.19465	0.04848	1.02	0.0913	1.055	0.0033194 Mo/ri		0	0.641	218	0 M5.5 V	2900	0.141	0.1221		5.16372 14h29m34.43s	217.3934857 -62d40m34.26s	-62.6761821	1.30119	11.01	4.364	8.95361	0.653942957
25	Kepler-445	1	3 Transit	2015 Kepler	0	8.15275	0.0439	1.25	0.11	2.1	0.0066 M-R relationship		0	4.314	305	0 M4	3157	0.21	0.19	0.27 [Fe/H]	4.82504 19h54m56.72s	298.7363395 +46d29m56.84s	46.4991236	127.291	18.19	12.61	16.7157	0.869954032
26	K2-3	1	3 Transit	2015 K2	0	44.55603	0.2014	1.458	0.13007427	2.2	0.00982197 Mass		0.091	1.44	305.2	0 M V	3844	0.546	0.549	-0.157 [Fe/H]	4.704 11h26m20.49s	172.3353708 -01d27m18.49s	-1.4551564	44.0727	12.188	8.561	11.4785	0.874749326
27	Kepler-442	1	1 Transit	2015 Kepler	0	112.3053	0.409	1.34	0.12	2.36	0.00742 M-R relationship		0.04	0.68	241	0	4402	0.598	0.629	-0.37 [Fe/H]	4.673 19h01m27.99s	285.3686229 +39d16m40.25s	39.2003704	365.965	15.322	12.468	14.9304	0.922132128
28	L 98-59	1	5 Radial Velocity	2025 Multiple Facilities	0	23.094	0.1052	1.48	0.132	2.8	0.00985979 Mo/ri		0.044	1.1	285	0 M3 V	3415	0.3155	0.2823	-0.46 [Fe/H]	4.91 08h16m07.89s	124.5238934 -68d18m52.38s	-68.3144858	10.8194	11.695	7.151	10.0376	0.933794922
29	LP 890-9	1	2 Transit	2022 SPECULOOS S	0	8.457463	0.03664	1.367	0.12195578	25.3	0.0796027 Mass			0.906	272	0 M6 V	2850	0.1556	0.118	-0.028 [Fe/H]	5.126 04h16m31.42s	64.1309396 -28d19m56.85s	-28.3157909	32.4266	18	11.344	15.8213	0.830954272
30	TOI-2095	1	2 Transit	2023 Transiting Exopl	0	28.17202	0.137	1.33	0.11665496	7.4	0.023263 Mass		0	1.84	297	0 M2.5 V	3759	0.44	0.44	-0.24 [Fe/H]	5.11 19h02m32.77s	285.6365235 +75d26m06.85s	75.4185135	41.9176	13.19	8.969	12.094	0.925713077
31	K2-72	1	4 Transit	2016 K2	0	24.158868	0.106	1.29	0.11508639	2.21	0.00896 M-R relationship		0.11	1.2	286.34	0	3360.47	0.330899	0.271385		5.048 22h19m29.49s	334.6227504 -09d59m43.23s	-9.6120984	66.4321	15.37	10.962	14.2783	0.875449309
32	TRAPPIST-1	1	7 Transit	2017 Multiple Observe	0	12.352446	0.04883	1.129	0.10072281	1.321	0.00415933 Mass		0.00208	0.252	197.3	1 M8.0 V	2566	0.1192	0.0898	0.052 [Fe/H]	5.2396 23h09m30.33s	346.6263019 -05d02m36.46s	-5.0434618	12.42988681	17.02	10.296	15.6451	0

Across the 30 planet dataset, ESI scores ranged from 0.67 ESI to 0.97, the range of values I analyzed.. The planets were then ranked based on the final scores to isolate the most promising worlds. The top 10 candidates were then selected, and then the top 5 worlds are highlighted to represent the most earthlike worlds based off of the ESI index

The top five green highlighted candidates have the earth index scores that are over 0.93 as this is the achieving near unity scores. These are the planets that have the least amount of deviations from terrestrial values. The top 10 scores were also extremely promising with ESI indexes over or equal to 0.90.

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Table 2 ESI Scores

Rank	Planet name	Interior ESI score
1	Kepler-438 b	0.9773389249
2	Kepler-1649 c	0.9565110925
3	Ross 128 b	0.943434084
4	TRAPPIST-1 f	0.9400260122
5	L 98-59 f	0.9337945622

➢ *Some Key Data Points Demonstrated by Our Analysis Include:*

- Kepler- 438b : This is the top ranking candidate with an interior ESI 0.97. It's a near perfect physical match with a favorable equilibrium EST of 276 K. This minimizes the mathematical penalties in the geometric formula.
- Candidates ranked 6th-10- these are promising candidates, they have an interior ESI score of 0.90 and above. They still demonstrate a high promise in terms of physical similarities.
- Variability : The database variability suggests that meeting the requirements and parameters in the database does not guarantee perfect earth similarities. For example the last planet in the database : K2-72 e has an interior ESI of 0.67, meaning the similarity is much less likely to support life.

➢ *Evaluation of Results:*

The result of this investigation shows that the mathematical similarity to earth does not guarantee habitability. While in my investigation Kepler-438 b has shown the highest mathematical similarity, due to its highly similar physical proportions, these scores must be evaluated from a border astrophysical point of view.

The main limitation with an ESI model is that it relies solely on bulk physical metrics, ignoring the atmospheric conditions of the planet itself :

- Stellar Activity and radiation : Kepler 438 b which was one of our top candidates sits next to a highly volatile M dwarf star which releases massive amounts of radiation, stripping it of its atmosphere, making it uninhabitable. (Armstrong et al., 2015) This example shows the limitation of this model. However these results are still valuable in helping us find a physical match to know what physical parameters we're looking for
- Atmospheric Composition : The ESI index only measures a planets physical similarity to earth and completely disregards the atmosphere of the planets. For example it ignores the atmosphere composition meaning a planet scoring 0.9 could be virtually uninhabitable due to the greenhouse gas particles

To reduce the limitations that come with just using ESI the next step would be to perform advanced spectroscopic studies on the high scoring planets, this will provide a definitive habitability test. This can be done through new age technology, for example the James Webb Space Telescope and the upcoming Nancy Grace Roman Space Telescope. (Gardner et al., 2006)

IV. CONCLUSION

In conclusion, in this study we have successfully evaluated the structural and geological habitability of terrestrial exoplanets, by implementing a two parameter interior ESI using NASA's exoplanet archive data. By implementing a filtering algorithm we have identified top tier candidates such as Kepler-438b, Kepler-1649c, and Ross 128b which closely mimic earth's physical architecture. However our mathematically close results don't guarantee habitability, however they provide a strong groundwork for future research in the area. In the future we must bridge the gap between interior modeling and atmospheric charachtarizaition.

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