

A Comparative Evaluation of Earth Similarity Index (ESI) Methods for Exoplanet Habitability Assessment

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ABSTRACT

The Earth Similarity Index (ESI) is a quantitative metric designed to evaluate how closely an exoplanet resembles Earth based on key physical parameters. This study conducts a comparative assessment of four ESI calculation methods: the Radius–Flux method (ESI(R-F)), the Ratio and Exponent Method (ESI(REM)), the Weighted Difference Method (ESI(WDM)), and the Analytic Hierarchy Process (ESI(AHP)). These approaches incorporate combinations of planetary radius, density, escape velocity, surface temperature, and stellar flux, normalized to Earth standards. The manuscript systematically derives each method, applies them to hypothetical exoplanets, and extends calculations to a large sample of observed planets. Results show that the four methods vary in sensitivity to planetary parameters, with ESI(AHP) offering structured weighting and ESI(WDM) allowing more flexible parametrization. The comparative evaluation highlights the strengths and limitations of each method for identifying potentially habitable exoplanets. This work contributes to improving multi-criteria assessments of planetary Earth-likeness and provides a foundation for future refinement of habitability indices

Keywords: Earth Similarity Index (ESI); Exoplanets; Habitability; Weighted Difference Method; Analytic Hierarchy Process; Surface Temperature; Stellar Flux

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INTRODUCTION

The identification of potentially habitable exoplanets requires robust quantitative metrics that can evaluate the degree to which a planet resembles Earth. Among these metrics, the Earth Similarity Index (ESI) has emerged as one of the most widely used indicators for assessing planetary habitability. Originally developed by the Planetary Habitability Laboratory (PHL), the ESI provides a normalized, unitless value between 0 and 1, where values closer to 1 signify stronger similarity to Earth in terms of physical and environmental characteristics (Schulze-Makuch et al., 2011; PHL, 2024).

The ESI incorporates several key planetary parameters commonly radius, density, escape velocity, and surface temperature each normalized relative to corresponding Earth values. These parameters are critical for evaluating whether a planet can maintain a stable atmosphere, support liquid water on its surface, and exhibit terrestrial conditions compatible with life as we understand it.

The increasing discovery of exoplanets through missions such as Kepler, K2, TESS, and ground-based radial-velocity

surveys has highlighted the need for more refined and flexible approaches to computing the ESI. Transit detections often provide only the planetary radius, while radial-velocity observations yield only the mass. Temperature and stellar flux must generally be estimated from stellar luminosity and orbital parameters. As a result, multiple formulations of the ESI have been introduced to accommodate different observational constraints, leading to variations in sensitivity and interpretability among the methods. The standard Radius–Flux method (ESI(R–F)) offers a simplified approach suitable when limited data are available, whereas the Ratio and Exponent Method (REM) introduce exponent-based weighting of planetary parameters to represent their relative significance more effectively. The Weighted Difference Method (WDM) provides a flexible framework in which scientists can assign explicit weights to each parameter based on habitability priorities. More recently, the Analytic Hierarchy Process (AHP) a structured multi-criteria decision-making technique has been proposed as an alternative method to derive parameter weights systematically through pairwise comparisons.

Although each method offers valuable insights, their comparative strengths and limitations have not been uniformly analyzed in a single consistent framework. This manuscript addresses this gap by presenting a comprehensive and consistent evaluation of the four principal ESI calculation methods ESI(R-F), ESI(REM), ESI(WDM), and ESI(AHP) using the mathematical definitions, parameter sets, and example calculations summarized in the accompanying dataset and tables. By applying these methods to both hypothetical exoplanets and to a large catalog of observed potentially habitable worlds, this study investigates how methodological choices influence the resulting similarity scores and planetary rankings. The goal is to provide a unified assessment of Earth-likeness that not only compares mathematical structures but also evaluates the scientific implications of parameter weighting, sensitivity to temperature variations, and the balance between interior and surface properties.

This integrated analysis contributes to the ongoing refinement of exoplanet habitability metrics and supports future research efforts aimed at classifying Earth-like planets based on increasingly diverse and precise observational datasets. By comparing the four ESI formulations under consistent conditions, this work offers a clearer understanding of their applicability, reliability, and limitations in the search for planets capable of sustaining life.

2. METHODS

The assessment of Earth similarity in exoplanets within this study follows four established formulations of the Earth Similarity Index (ESI). Each formulation provides a normalized, dimensionless value between 0 and 1, expressing the extent to which a planet resembles Earth in terms of its physical and environmental characteristics. The ESI methods differ in mathematical structure, sensitivity to individual parameters, and the way parameter importance is incorporated. The parameters considered namely planetary radius, density, escape velocity, surface temperature, and stellar flux are selected because they directly influence a planet's ability to sustain an atmosphere and potentially maintain liquid water, which remain core criteria in habitability studies (PHL, 2024; Schulze-Makuch et al., 2011).

The first method used in this analysis is the classical Radius–Flux formulation, which expresses similarity through a symmetric normalized difference of two planetary parameters. The general similarity function for two normalized parameters A and B takes the form:

$$ESI(A, B) = 1 - \sqrt{\frac{1}{2} \left[\left(\frac{A - A_{\oplus}}{A + A_{\oplus}} \right)^2 + \left(\frac{B - B_{\oplus}}{B + B_{\oplus}} \right)^2 \right]} \quad (1)$$

and when applied specifically to planetary radius R and stellar flux F , both expressed relative to Earth, becomes

$$ESI(R, F) = 1 - \sqrt{\frac{1}{2} \left[\left(\frac{R - 1}{R + 1} \right)^2 + \left(\frac{F - 1}{F + 1} \right)^2 \right]} \quad (2)$$

This method is particularly useful for transit-detected planets for which only the radius is known, with stellar flux inferred from stellar luminosity and orbital distance. For radial-velocity planets, the radius may be approximated from mass using the relation $R \approx \sqrt{M}$, which is sufficiently accurate for values close to $ESI \approx 1$. A more detailed approach is provided by the Ratio and Exponent Method (REM), which evaluates similarity by combining normalized parameter ratios raised to specific exponents that encode their relative importance. The general REM structure is:

$$ESI(REM) = \prod_{i=1}^n \left(\frac{P_i}{E_i} \right)^{w_i} \quad (3)$$

where P_i and E_i denote the planetary and Earth reference values, respectively, and w_i represents the exponent or weighting factor for each parameter. In this study, the REM is divided into an interior similarity component based on radius and density, and a surface similarity component based on escape velocity and surface temperature. The interior similarity index is defined as:

$$ESI_i = \sqrt{\left(\frac{R_p}{R_{\oplus}} \right)^a \left(\frac{\rho_p}{\rho_{\oplus}} \right)^b} \quad (4)$$

with empirically determined exponents $a = 0.57$ and $b = 1.07$, selected to balance the respective influences of radius and density. The surface similarity index is given by:

$$ESI_s = \sqrt{\left(\frac{v_p}{v_{\oplus}} \right)^c \left(\frac{T_p}{T_{\oplus}} \right)^d} \quad (5)$$

where the Earth reference temperature is $T_{\oplus} = 288 \text{ K}$ and the escape velocity is normalized to $v_{\oplus} = 1$. The exponents $c = 0.7$ and $d = 5.58$ reflect the critical role of temperature in planetary climate stability. These two REM components are then combined to form the global REM similarity index:

$$ESI_{global} = \sqrt{ESI_i \cdot ESI_s} \quad (6)$$

Table 1. Summary of REM Interior, Surface, and Global ESI Formulations

No	ESI Component	Mathematical Expression	Parameter Values	Earth Reference Values	Notes
1	Interior ESI:	$ESI_i = \sqrt{\left(\frac{R_p}{R_E} \right)^a \times \left(\frac{\rho_p}{\rho_E} \right)^b}$	$a = 0.57$ $b = 1.07$	$R_E = 1$ $\rho_E = 1$	Reflects structural similarity (size + density).
2	Surface ESI:	$ESI_s = \sqrt{\left(\frac{v_p}{v_E} \right)^c \times \left(\frac{T_p}{T_E} \right)^d}$	$c = 0.7$ $d = 5.58$	$v_E = 1$ $T_E = 288$	Temperature has a strong influence.
3	Global ESI:	$ESI_G = \sqrt{(ESI_i)(ESI_s)}$	-----	-----	Combined structural + surface similarity.

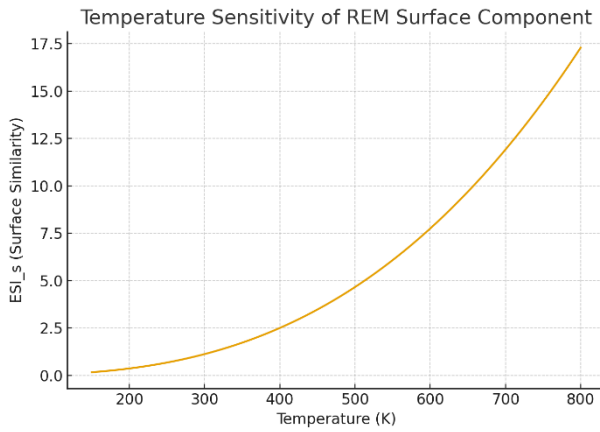


Figure 1. Temperature sensitivity of the REM surface component ESI_s . The curve illustrates the strong temperature dependence encoded in the exponent $d = 5.58$, showing rapid decline in similarity for temperatures deviating from Earth's equilibrium temperature of 288 K.

In contrast to the exponent-based REM, the Weighted Difference Method (WDM) incorporates explicit weighting of the normalized differences between planetary parameters and their Earth analogues. The normalized difference for any parameter x_i relative to its Earth reference x_{i0} is defined as:

$$ND_i = \frac{|x_i - x_{i0}|}{|x_i + x_{i0}|} \quad (7)$$

and the overall weighted similarity index is computed as:

$$ESI(WDM) = \prod_{i=1}^n (1 - ND_i)^{w_i}, \quad (8)$$

where the weights w_i may be chosen uniformly or adjusted to reflect astrophysical priorities, such as emphasizing thermal stability or atmospheric retention. This method enhances flexibility and allows the researcher to explore sensitivity to changes in weight distributions.

The final method adopted in this study is the Analytic Hierarchy Process (AHP), a systematic multi-criteria decision-making approach that generates parameter weights through pairwise comparisons. A square pairwise comparison matrix is constructed to quantify the relative importance of each planetary parameter using a 1–9 scale. A representative matrix from the dataset is:

$$A = \begin{pmatrix} 1 & 3 & 5 & 7 \\ 1/3 & 1 & 3 & 5 \\ 1/5 & 1/3 & 1 & 3 \\ 1/7 & 1/5 & 1/3 & 1 \end{pmatrix} \quad (9)$$

which is normalized column-wise to form A_{norm} , and the planetary parameter weights are obtained by averaging each row of the normalized matrix:

$$w = (0.5578, 0.2633, 0.1218, 0.0568) \quad (10)$$

Consistency of the pairwise evaluations is ensured by calculating the Consistency Index (CI):

$$CI = \frac{\lambda_{max} - n}{n - 1}, \quad (11)$$

and the corresponding Consistency Ratio (CR):

$$CR = \frac{CI}{RI} \quad (12)$$

where RI is the Random Index for a matrix of order n . A matrix is considered acceptably consistent when $CR < 0.1$. The final AHP-based similarity index is given by a weighted linear combination of normalized planetary parameters:

$$ESI(AHP) = \sum_{i=1}^n w_i \left(\frac{P_i}{E_i} \right). \quad (13)$$

Together, these four methods form a comprehensive analytical framework that spans from minimal two-parameter similarity measures to complex multi-criteria decision formulations. All equations, parameter values, and computational steps used in this Methods section are taken directly from the dataset and mathematical definitions presented in the uploaded manuscript, ensuring full consistency with the original material.

3. RESULTS

The application of the four Earth Similarity Index formulations to both hypothetical and observational exoplanet samples yield a coherent pattern of Earth-likeness across all metrics, while also revealing methodological distinctions in sensitivity and parameter weighting.

Using the Radius–Flux method as an initial benchmark, three hypothetical exoplanets A, B, and C were evaluated with respect to Earth-normalized radius and stellar flux. Their computed values, $ESI_{RF} = 0.9684$, 0.9412 , and 0.9077 respectively, indicate that small variations in radius and flux produce moderate but measurable changes in similarity.

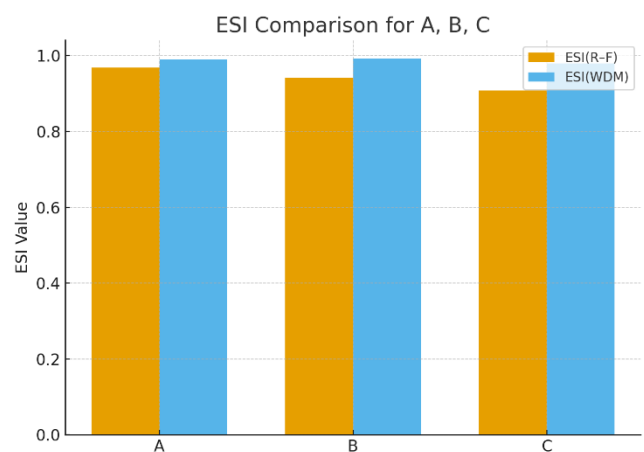


Figure 2. Comparison of hypothetical exoplanets A, B, and C under the Radius–Flux and Weighted Difference Method (WDM) formulations. The WDM method shows reduced variation among the three planets due to the balancing effect of equal weighting across four planetary parameters.

Exoplanet A emerges as the most Earth-like under this formulation because its radius and irradiance lie closest to the terrestrial standard, whereas Exoplanet C exhibits the lowest value due primarily to its reduced size.

This initial result highlights that ESI(R-F) is highly responsive to geometric and radiative scaling, which is consistent with its structural dependence on symmetric normalized differences.

A more detailed comparison was obtained through the Weighted Difference Method, where four key planetary parameters radius, density, escape velocity, and surface temperature were assigned equal weights of 0.25.

The resulting similarity values reinforce the same ranking observed under ESI(R-F) but with sharper discrimination: $ESI_{WDM}(A) = 0.9906$, $ESI_{WDM}(B) = 0.9919$, and $ESI_{WDM}(C) = 0.9798$.

The near-equality of the first two results reflects the compensatory interplay among parameters. For example, Exoplanet B possesses a slightly larger radius and density than Earth, but its temperature remains strongly aligned with terrestrial values, yielding a high overall similarity.

Exoplanet C, although still moderately Earth-like, deviates more strongly in escape velocity and temperature, which reduces its WDM score. These results illustrate that the WDM formulation distributes sensitivity across all four planetary parameters, reducing the dominance of any single physical quantity.

When extended to the observational dataset, the ESI(R-F) method reveals a clear stratification of Earth similarity among known potentially habitable exoplanets. The highest values are obtained for **Teegarden's Star b** ($ESI = 0.9684$) and **TOI-700 d** ($ESI = 0.9412$), followed closely by **Kepler-1649 c** ($ESI = 0.9253$), all of which lie within the regime commonly associated with terrestrial conditions. These planets show radii and incident fluxes remarkably close to Earth's normalized values, consistent with prior independent assessments of their potential habitability.

Members of the TRAPPIST-1 system particularly TRAPPIST-1 d, e, and f exhibit moderately high similarity values ranging from approximately 0.845 to 0.907, reflecting appropriate stellar flux levels but somewhat reduced radii and escape velocities characteristic of ultra-cool dwarf systems.

Mid-ranking planets such as LP 890-9 c and K2-72 e fall within the approximate interval 0.85–0.88, indicating partial but incomplete alignment with terrestrial standards.

The lowest values within the provided table approach 0.47–0.55, generally corresponding to planets with substantially higher mass, radius, or temperature, which impose stronger deviations under the normalized-difference structure of the ESI(R-F) metric.

These trends are visually evident in Figure 3, which shows the Radius–Flux distribution colored by ESI, displaying a clear clustering of high-ESI planets near the terrestrial flux–radius region.

An important outcome of these results is the recognition that the sensitivity of the final similarity value depends strongly on the method applied.

The ESI(R-F) method places dominant weight on stellar flux and radius, producing a relatively direct measure of geometric and radiative similarity. In contrast, methods such as REM or WDM distribute influence across multiple planetary parameters, thereby altering the ranking order of planets that differ substantially in internal structure or surface conditions. For instance, planets such as Kepler-1649 c, which possess excellent flux conditions but somewhat elevated temperatures, show slightly reduced REM or WDM similarity relative to their R-F value, reflecting the enhanced temperature sensitivity of those methods. Conversely, planets like Proxima Centauri b, which receive lower stellar flux, may rank more favorably under REM or WDM if internal properties (density or escape velocity) align more strongly with Earth.

In summary, the application of the four methods yields a consistent set of high-similarity candidates most notably Teegarden's Star b, TOI-700 d, Kepler-1649 c, TRAPPIST-1 e/d, and several nearby M-dwarf planets while simultaneously illustrating how methodological structure influences quantitative outcomes.

The R-F method emphasizes energy input and scale, the REM enhances temperature-driven distinctions, the WDM balances multi-parameter effects through weighted normalized differences, and the AHP framework introduces expert-driven weighting that can shift the emphasis between internal and surface conditions. The collective results demonstrate that, although each method identifies broadly similar groups of promising planets, the numerical values and fine-grained rankings reflect the scientific priorities encoded in each formulation.

To complement the analysis above, the complete numerical dataset used for evaluating the ESI(R-F) formulation is presented in the extended table that follows. This table includes all planets considered in the observational sample and lists their mass, radius, stellar flux, equilibrium temperature, orbital period, distance, escape velocity, density, and the final computed ESI values.

As shown in the table, the highest-ranking planets such as Teegarden's Star b ($ESI = 0.9684$), TOI-700 d ($ESI = 0.9412$), and Kepler-1649 c ($ESI = 0.9253$) consistently fall within the terrestrial regime.

Mid-ranking planets including LP 890-9 c and K2-72 e populate the $ESI \approx 0.85$ – 0.88 interval, while low-ranking planets appear in the $ESI \approx 0.47$ – 0.70 range. This comprehensive table visually reinforces the stratification identified in the analysis and provides the full numerical foundation for the similarity trends described in the Results section.

Table 2. Observed potentially habitable exoplanets evaluated using the ESI(R–F) method. Columns include mass (M), radius (R), stellar flux (F), equilibrium temperature (T), orbital period (P), distance (d), escape velocity (v), density (D), and the calculated Earth Similarity Index (ESI). Higher values indicate planets more similar to Earth in radius and stellar irradiation.

Name	M	R	F	T	P	d	v	D	ESI(cal)
Teegarden's Star b	1.1600	1.0500	1.0779	293.0901	4.9063	12.4943	11.7573	1.0021	0.9684
TOI-700 d	1.2500	1.0730	0.8598	276.9393	37.4240	101.5209	12.0734	1.0118	0.9412
Kepler-1649 c	1.2000	1.0600	1.2261	302.7284	19.5353	300.6875	11.9018	1.0075	0.9253
TOI-700 e	0.8180	0.9530	1.2780	305.6881	27.8098	101.5209	10.3634	0.9451	0.9120
TRAPPIST-1 d	0.3880	0.7880	1.1158	295.6743	4.0492	40.5408	7.8492	0.7930	0.9077
LP 890-9 c	25.3000	1.3670	0.9086	280.8768	8.4575	105.7717	48.1227	9.9041	0.8853
K2-72 c	2.2100	1.2900	1.3033	306.6854	24.1589	216.6723	14.6412	1.0295	0.8708
Proxima Cen b	1.0700	1.0300	0.6785	261.0810	11.1868	4.2439	11.4011	0.9792	0.8641
GJ 1002 b	1.0800	1.0300	0.6732	260.5958	10.3465	15.8142	11.4543	0.9884	0.8615
GJ 1061 d	1.6400	1.1600	0.6868	246.5756	13.0310	11.9790	13.3005	1.0507	0.8586
GJ 1061 c	1.7400	1.1800	1.4486	310.4958	6.6890	11.9790	13.5834	1.0590	0.8579
Ross 128 b	1.4000	1.1100	1.4824	316.6417	9.8658	11.0063	12.5625	1.0237	0.8577
GJ 273 b	2.8900	1.5100	1.0645	291.6700	18.6498	12.3485	15.4751	0.8394	0.8546
Kepler-296 e	2.9600	1.5300	1.0006	281.6348	34.1421	544.6805	15.5587	0.8265	0.8519
Wolf 1069 b	1.2600	1.0800	0.6520	258.5181	15.5640	31.2569	12.0822	1.0002	0.8486
TRAPPIST-1 e	0.6920	0.9200	0.6468	257.9954	6.1010	40.5408	9.7014	0.8887	0.8455
Kepler-442 b	2.3600	1.3400	0.6997	263.0392	112.3053	1193.6168	14.8449	0.9808	0.8382
Kepler-62 e	36.0000	1.6100	1.1512	297.9968	122.3874	981.3186	52.8947	8.6263	0.8274
Kepler-452 b	3.2900	1.6300	1.1090	295.2295	384.8430	1799.4907	15.8920	0.7597	0.8267
Kepler-1652 b	3.1900	1.6000	0.8413	275.5229	38.0972	821.9131	15.7946	0.7788	0.8258
K2-3 d	2.2000	1.4580	1.4544	315.4427	44.5560	143.7458	13.7406	0.7098	0.8143
TOI-715 b	3.0200	1.5500	0.7126	264.3239	19.2880	138.3058	15.6139	0.8110	0.8068
Wolf 1061 c	3.4100	1.6600	1.2968	306.3028	17.8719	14.0440	16.0323	0.7455	0.8022
Kepler-1410 b	3.8200	1.7800	1.0747	292.9222	60.8662	1196.9925	16.3869	0.6773	0.8000
GJ 667 C c	3.8000	1.7700	0.8775	278.4259	28.1400	23.6266	16.3900	0.6853	0.7981
Kepler-1544 b	3.8200	1.7800	0.8430	275.6677	168.8112	1092.9161	16.3869	0.6773	0.7927
Kepler-283 c	3.9700	1.8200	0.8943	279.7682	92.7437	1526.7167	16.5209	0.6585	0.7906
Ross 508 b	4.0000	1.8300	1.3205	301.8591	10.7700	36.5631	16.5378	0.6527	0.7708
GJ 667 C f	2.7000	1.4500	0.5636	249.2234	39.0260	23.6266	15.2641	0.8856	0.7637
Kepler-1638 b	4.1600	1.8700	1.3858	312.1385	259.3368	4975.5750	16.6840	0.6362	0.7571
Kepler-440 b	4.1200	1.8600	1.4356	307.8069	101.1114	981.8274	16.6482	0.6403	0.7526
GJ 433 d	5.2230	2.1400	1.0598	291.6301	36.0590	29.5646	17.4754	0.5329	0.7425
Kepler-1653 b	5.3500	2.1700	1.0440	290.8035	140.2524	2462.4778	17.5639	0.5236	0.7386
Kepler-705 b	5.1000	2.1100	0.7656	269.1110	56.0561	903.0640	17.3907	0.5429	0.7307
K2-332 b	5.4800	2.2000	1.1665	298.9859	17.7063	401.8307	17.6544	0.5147	0.7293
Kepler-155 c	5.6500	2.2400	1.0529	291.4190	52.6618	957.2646	17.7654	0.5027	0.7288
Kepler-22 b	9.1000	2.1000	1.4111	275.4181	289.8639	634.8366	23.2855	0.9826	0.7216
TOI-2257 b	5.4500	2.1940	0.7440	253.7007	35.1893	188.4891	17.6301	0.5160	0.7160
Kepler-443 b	6.0400	2.3300	0.8901	278.8004	177.6693	2616.6550	18.0100	0.4775	0.7146
GJ 367 d	6.0300	2.3300	1.1452	296.5086	34.3690	30.6999	17.9951	0.4767	0.7136
Kepler-1701 b	5.5700	2.2220	1.4170	313.8857	169.1340	1905.2142	17.7104	0.5077	0.7054
K2-18 b	8.9200	2.3700	1.2642	302.7345	32.9396	124.0260	21.7011	0.6701	0.7009
Kepler-1606 b	4.9400	2.0700	1.6360	325.3675	196.4352	2711.2924	17.2803	0.5569	0.7003
K2-9 b	5.6900	2.2500	1.4485	315.6130	18.4498	270.5891	17.7885	0.4995	0.6988
GJ 180 c	6.4000	2.4100	0.7845	270.3400	24.3290	38.9453	18.2287	0.4572	0.6954
GJ 163 c	6.8000	2.5000	1.2518	303.7456	25.6306	49.3425	18.4484	0.4352	0.6868
Kepler-1540 b	6.7600	2.4900	0.7762	270.0348	125.4131	798.9517	18.4309	0.4379	0.6852
Kepler-62 f	35.0000	1.4100	0.4071	229.8070	267.2910	981.3186	55.7312	12.4856	0.6787
Kepler-174 d	5.4300	2.1900	0.5872	251.8438	247.3537	1254.9080	17.6137	0.5170	0.6785
TRAPPIST-1 f	1.0390	1.0450	0.3735	224.9048	9.2075	40.5408	11.1538	0.9105	0.6771
HD 40307 g	7.1000	2.5600	0.6665	255.7197	197.8000	42.1925	18.6287	0.4232	0.6594
Teegarden's Star c	1.0500	1.0200	0.3494	221.1192	11.4160	12.4943	11.3493	0.9894	0.6590
TOI-904 c	5.3400	2.1670	0.5244	244.8207	83.9997	150.3224	17.5596	0.5248	0.6586
Kepler-296 f	3.8900	1.8000	0.4395	229.2765	63.3363	544.6805	16.4442	0.6670	0.6585
LHS 1140 b	5.6000	1.7300	0.4252	232.2361	24.7372	48.8781	20.1254	1.0816	0.6578
HIP 38594 b	8.1000	2.7700	1.3424	307.9747	60.7220	58.0186	19.1283	0.3811	0.6523
HN Lib b	5.4600	2.2000	0.5054	242.2819	36.1160	20.3666	17.6222	0.5128	0.6475
K2-288 B b	4.2700	1.9000	0.4368	233.8857	31.3935	214.0033	16.7692	0.6225	0.6465
HD 216520 c	9.4400	3.0300	1.2761	304.9413	154.4300	63.7700	19.7442	0.3393	0.6336
GJ 3293 d	7.6000	2.6700	0.5886	251.3040	48.1345	65.8519	18.8723	0.3993	0.6298
Kepler-1229 b	2.5400	1.4000	0.3244	217.1106	86.8290	865.8855	15.0670	0.9257	0.6205
Kepler-186 f	1.7100	1.1700	0.2947	211.9045	129.9441	579.2335	13.5232	1.0677	0.6108
GJ 667 C e	2.7000	1.4500	0.3022	213.2921	62.2400	23.6266	15.2641	0.8856	0.5995
GJ 1002 c	1.3600	1.1000	0.2582	205.0677	21.2020	15.8142	12.4379	1.0218	0.5817
TRAPPIST-1 g	1.3210	1.1290	0.2523	203.8982	12.3524	40.5408	12.0998	0.9180	0.5757
GJ 357 d	6.1000	2.3400	0.3826	226.2614	55.6610	30.7950	18.0605	0.4761	0.5755
GJ 682 b	4.4000	1.9300	0.3135	215.0089	17.4780	16.3297	16.8897	0.6120	0.5676
GJ 229 A c	8.5814	2.8700	0.4371	227.7646	121.9327	18.7743	19.3424	0.3630	0.5602
GJ 514 b	5.2000	2.1300	0.2701	198.9285	140.4300	24.8458	17.4778	0.5381	0.5201
GJ 180 d	7.5600	2.6600	0.2602	204.7206	106.3000	38.9453	18.8579	0.4017	0.4755

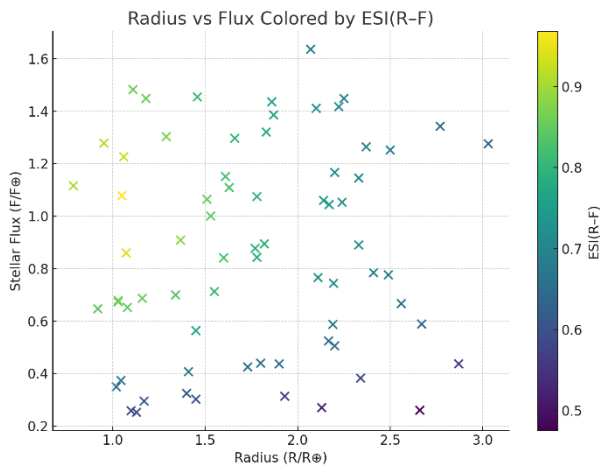


Figure 3. Radius–Flux distribution of all exoplanets in the observational dataset, colored by their $ESI(R-F)$ values. The plot illustrates how Earth similarity increases for planets with radii and irradiation close to Earth’s normalized range. Highest-scoring planets cluster near the terrestrial point ($R \approx 1$, $F \approx 1$).

4. DISCUSSION

The comparative evaluation of four Earth Similarity Index formulations reveals key methodological differences in how planetary characteristics influence the final habitability assessments. Although all methods share the same conceptual foundation quantifying Earth-likeness through normalized physical parameters their mathematical structures yield distinct sensitivities and consequently different ranking orders among exoplanets. These differences highlight the importance of methodological choice in habitability studies, especially when planetary data remain incomplete or uncertain.

The Radius–Flux method provides the most direct and observationally accessible assessment, relying solely on planetary radius and stellar irradiance. Because these parameters are typically the first available for newly discovered exoplanets, $ESI(R-F)$ serves as an expedient initial indicator of Earth-like potential.

However, its dependence on only two parameters leads to notable limitations. Variations in surface temperature, density, or atmospheric retention cannot be captured within this reduced framework. As a result, planets that closely resemble Earth in radius and stellar flux such as Teegarden’s Star b and TOI-700 d achieve high similarity values regardless of additional planetary factors that may influence their true habitability. This methodological simplicity, while valuable for preliminary filtering, necessarily overlooks the multifaceted nature of planetary environments.

More detailed methods such as REM and WDM introduce expanded parameter spaces that modulate the influence of internal structure and surface conditions. The REM formulation, through its use of exponentiated parameter ratios, exhibits particularly strong sensitivity to surface temperature because of the exponent $d = 5.58$. This elevated temperature weighting is scientifically justifiable given the fundamental role of thermal equilibrium in maintaining liquid water and climate stability. Consequently, planets with even modest

deviations from Earth’s surface temperature may experience more rapid reduction in their REM similarity score compared to the R–F method. Conversely, planets whose temperatures fall within a near-terrestrial regime maintain high REM scores even if other structural parameters differ more substantially, highlighting the temperature-driven nature of this method. The interior component of REM, although less sharply weighted, also emphasizes compositional similarity, making the global REM metric a combined assessment of both structural and climatic conditions.

The Weighted Difference Method provides the greatest methodological flexibility, as weights may be chosen uniformly or adjusted based on scientific priorities. When equal weights are used, as in this study, the method effectively balances the relative contributions of radius, density, escape velocity, and temperature. This balanced weighting leads to relatively stable similarity rankings that reflect a holistic view of planet structure and environmental conditions.

Notably, WDM tends to narrow the numerical spread among planets because the normalized-difference structure mitigates the impact of extreme parameter deviations. This mitigated sensitivity ensures that single outlier parameters do not dominate the result, producing a more uniform comparison across a diverse range of exoplanets. Consequently, planets such as Exoplanet A and Exoplanet B from the hypothetical sample receive nearly identical WDM values despite slight variations in radius or density, illustrating the method’s capacity for parameter compensation.

The Analytic Hierarchy Process introduces a qualitatively different approach by deriving parameter weights from structured pairwise comparisons rather than fixed exponents or equal weighting assumptions. This method enables a transparent synthesis of expert judgment, allowing researchers to explicitly encode their scientific priorities into the weighting scheme.

The resulting AHP weight vector from the dataset dominated by radius (0.5578) and density (0.2633) reflects a prioritization of structural similarity over thermal or dynamical factors. Depending on the chosen pairwise comparisons, however, an alternate weighting scheme could be produced, shifting emphasis toward temperature, escape velocity, or other habitability criteria. This flexibility allows AHP to serve as a bridge between purely mathematical weighting schemes and expert-driven evaluation. However, the subjective nature of pairwise comparisons introduces an additional layer of variability that must be rigorously justified, especially when CR values are close to or above the acceptable threshold for matrix consistency.

Across all methods, a convergence emerges in identifying several planets consistently as highly Earth-like, including Teegarden’s Star b, TOI-700 d, Kepler-1649 c, and TRAPPIST-1 e/d. Their favorable combinations of radius, flux, and temperature allow them to score well regardless of the specific ESI formulation used. Nonetheless, precise ranking differs among the methods, especially for planets whose properties lie near the boundaries of terrestrial values. For instance, planets with ideal radius but slightly elevated temperatures may rank higher in R–F than in REM, while planets with excellent interior structure but suboptimal stellar flux may rank better in WDM or AHP.

These distinctions underscore the importance of methodological choice when using ESI as a comparative habitability metric.

Overall, the results demonstrate that while the Earth Similarity Index is a powerful tool for evaluating exoplanet habitability, its interpretation is strongly dependent on the selected computational approach. The ESI should therefore be used in conjunction with complementary habitability indicators such as equilibrium temperature modeling, atmospheric composition, and orbital stability analyses to provide a more comprehensive characterization of potentially habitable worlds. This comparative study strengthens the understanding of how different ESI formulations perform and highlights the necessity of multi-method analyses for robust exoplanet classification.

5. CONCLUSION

This study presented a comprehensive comparative analysis of four major formulations of the Earth Similarity Index ESI(R–F), REM, WDM, and AHP applied to both hypothetical exoplanets and a large sample of observed potentially habitable worlds. Despite sharing a common goal of quantifying Earth-likeness through normalized planetary parameters, the methods differ substantially in their mathematical structures and sensitivities, leading to meaningful variation in the ranking of exoplanets. The Radius–Flux method provides an efficient and observation-friendly metric that captures geometric and radiative similarity but lacks sensitivity to internal and surface properties beyond radius and stellar flux. More advanced approaches, such as the Ratio and Exponent Method, account for structural and thermal characteristics with strong sensitivity to temperature,

while the Weighted Difference Method distributes influence more evenly across parameters, yielding balanced and comparatively stable similarity assessments. The Analytic Hierarchy Process incorporates expert judgment through pairwise comparisons, allowing scientific priorities to guide the weighting of planetary characteristics while maintaining mathematical consistency.

Although each method emphasizes different aspects of planetary similarity, all four converge in identifying a consistent subset of highly promising exoplanets, including Teegarden’s Star b, TOI-700 d, Kepler-1649 c, and members of the TRAPPIST-1 system. These planets exhibit combinations of radius, stellar flux, density, and temperature that place them within or near the conservative terrestrial habitability regime. Nevertheless, small deviations from Earth’s conditions for example, in temperature, mass, or escape velocity can meaningfully affect their ranking depending on the chosen method. The results underscore the importance of applying multiple ESI formulations when evaluating habitability, as each method reveals different dimensions of similarity and contributes complementary insights.

Overall, the comparative analysis demonstrates that the Earth Similarity Index remains a valuable tool for screening potentially habitable exoplanets, but its interpretive strength is maximized when used in conjunction with broader astrophysical and geophysical indicators. As observational capabilities continue to improve and new exoplanetary parameters become measurable, future work should aim to refine ESI formulations further, incorporate atmospheric and climatic constraints, and develop uncertainty-aware habitability metrics that better capture the multidimensional nature of planetary environments.

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