Supplementary Information

Comparative life cycle assessment study of virgin polyethylene and bio-polyethylene, with recycled polyethylene from uncontaminated post-industrial film

Authors: Ahdo Kim[1#], Teuku Naraski Zahari[2#], Nobuteru Edayoshi[3], Pin Juo Chou[3,4], Toshiki Yamamoto[3], Pin Yen Chou[3,4], Kei Saito[1]*, Benjamin McLellan[2]*

1. Graduate School of Advanced Integrated Studies in Human Survivability, Kyoto University Higashi-Ichijo-Kan, Yoshida-nakaadachicho 1, Sakyo-ku, Kyoto, 606-8306, Japan

2. Graduate School of Energy Science, Kyoto University, Yoshida Campus, Yoshida-Honmachi, Sakyo-Ku, Kyoto, 606-8501, Japan

3. esa Inc. SOC Takanawa Building 8F, 3-19-26 Takanawa, Minato-ku, Tokyo, 108-0074, Japan

4. Chuang Tieh Machine, No.6 Chong Shin Road, Tree Valley Park. Tainan, 74148, Taiwan

*Corresponding author e-mail: mclellan.benjamincraig.7v@kyoto-u.ac.jp and saito.kei.1y@kyoto-u.ac.jp

# Ahdo Kim and Teuku Naraski Zahari contributed equally to this work

Table S1: Mechanical properties of mixing materials of Repla™ and Virgin-PE

	Unit	Materials	Repla™ : Virgin-PE			Standard value
		Mixing rate	87:23	60:40	40:60	
Seal strength	N [kgf]	normal section	6	8	9	8
		gusset section	13	14	14	14
Tensile strength	MPa	vertical	26	29	30	29
		horizontal	30	30	31	29
Tensile strength	%	vertical	241	237	183	150
		horizontal	558	582	592	150

Table S2: Inventory analysis data of Scenario 1

Scenario 1 Plastic Bag (100% Virgin PE, VN)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	1000	kg
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	200	tkm
	Transport, Freight, Container Ship (sea transportation between Vietnam and Japan)	9948	tkm
	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (VN)	400	kWh

Table S3: Inventory analysis data of Scenario 2

Scenario 2 Plastic Bag (50% Virgin PE, 50% Bio-PE, VN)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	500	kg
	Bio-PE	500	kg
	Transport, Freight, Lorry, EURO5 (domestic transportation in Brazil)	50	tkm
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	150	tkm
	Transport, Freight, Container Ship (sea transportation between Brazil, Vietnam and Japan)	17813	tkm
	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (VN)	400	kWh

Table S4: Inventory analysis data of Scenario 3

Scenario 3 Plastic Bag (50% Virgin PE, 50% Repla™, VN)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	500	kg
	Repla™	500	kg
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	150	tkm
	Transport, Freight, Container Ship (sea transportation between Vietnam and Japan)	9948	tkm

	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (VN)	400	kWh

Table S5: Inventory analysis data of Scenario 4

Scenario 4 Plastic Bag (100% Virgin PE, JP)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	1000	kg
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	200	tkm
	Transport, Freight, Container Ship (sea transportation between Vietnam and Japan)	9948	tkm
	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (JP)	400	kWh

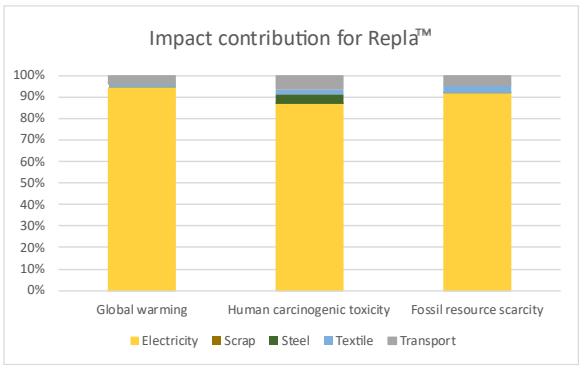
Table S6: Inventory analysis data of Scenario 5

Scenario 5 Plastic Bag (50% Virgin PE, 50% Bio-PE, JP)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	500	kg
	Bio-PE	500	kg
	Transport, Freight, Lorry, EURO5 (domestic transportation in Brazil)	50	tkm
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	150	tkm
	Transport, Freight, Container Ship (sea transportation between Brazil, Vietnam and Japan)	17813	tkm

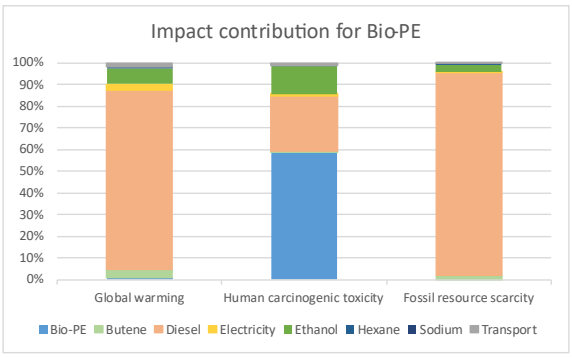
	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (JP)	400	kWh

Table S7: Inventory analysis data of Scenario 6

Scenario 6 Plastic Bag (50% Virgin PE, 50% Repla™, JP)			
	Flows	Amount	Unit
Output			
	Plastic bag	1000	kg
Inputs			
	Virgin PE	500	kg
	Repla™	500	kg
	Transport, Freight, Lorry, EURO6 (domestic transportation in Japan)	150	tkm
	Transport, Freight, Container Ship (sea transportation between Vietnam and Japan)	9948	tkm
	Transport, Freight, Lorry 3.5-7.5 metric ton, EURO3 (domestic transportation in Vietnam)	40	tkm
	Electricity, High Voltage (JP)	400	kWh



(a)



(b)

Figure S1: Process Impact Contribution for (a) Repla™ and (B) Bio-PE

Table S8: Pedigree matrix

Dimensions	Score	
Reliability (Verified means: published in public environment reports of compagnies, official statistics, etc. Unverified means: personal information by letter, fax or e-mail)	1	Verified data based on measurements
	2	Verified data partly based on assumptions or non-verified data based on measurements
	3	Non-verified data partly based on qualified estimates
	4	Qualified estimate (e.g. by industrial expert)
	5	Non-qualified estimated
Completeness (Length of adequate period depends on process/technology)	1	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations
	2	Representative data from >50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations
	3	Representative data from only some sites (<<50%) relevant for the market considered or >50% of sites but from shorter periods
	4	Representative data from only one site relevant for the market considered or some sites but from shorter periods
	5	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation (Score for processes with investment cycles of <10 year. For other cases, scoring adjustments can be made accordingly.)	1	Less than 3 years of difference to the time period of the dataset
	2	Less than 6 years of difference to the time period of the dataset
	3	Less than 10 years of difference to the time period of the dataset
	4	Less than 15 years of difference to the time period of the dataset
	5	Age of data unknown or more than 15 years of difference to the time period of the dataset
Geographical correlation	1	Data from area under study

(Similarity expressed in terms of environmental legislation. Suggestion for grouping: - North America, Australia - European Union, Japan, South Africa - South America, North and central Africa and Middle east - Russia, China, Far East Asia)	2	Average data from larger area in which area under study is included
	3	Data from area with similar production conditions
	4	Data from area with slightly similar production conditions
	5	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)
Further technological correlation (Examples for different technology: - steam turbine instead of motor propulsion in ships - emission factor B(a)P for diesel train based on lorry motor data Examples for related processes or materials - data for tyles instead of bricks production - data of refinery infrastructure for chemical plants infrastructure)	1	Data from enterprises, processes and materials under study
	2	Data from processes and materials under study (i.e. Identical technology) but from different enterprises
	3	Data from processes and materials under study but from different technology
	4	Data on related processes or materials
	5	Data on related processes on laboratory scale or from different technology

Table S9: Uncertainties of each input based on pedigree matrix

	Virgin-PE	Bio-PE	Repla™	Transportation	Electricity for manufacturing
Reliability	1	2	4	4	4
Completeness	1	1	4	1	4
Temporal correlation	1	1	1	1	1
Geographical correlation	1	1	1	1	1
Further technological correlation	1	1	1	1	1
Total uncertainty (Basic uncertainty)	1.05 (1.05)	1.07 (1.05)	1.24 (1.05)	1.21 (1.05)	1.24 (1.05)

Table S10: Uncertainty analysis (Monte Carlo simulations) results for all impact categories

SC1								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	9.444559	9.440847	0.219131	2.320186	9.025981	9.885043	0.002191
Terrestrial ecotoxicity	kg 1,4-DCB	6584.317	6581.796	139.4166	2.117405	6320.596	6865.673	1.394166
Terrestrial acidification	kg SO2 eq	11.18886	11.18124	0.290245	2.59405	10.63214	11.78273	0.002902
Stratospheric ozone depletion	kg CFC11 eq	0.00059	0.00059	1.38E-05	2.344976	0.000564	0.000618	1.38E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	9.298362	9.294626	0.223312	2.401628	8.867858	9.748569	0.002233
Ozone formation, Human health	kg NOx eq	8.830919	8.827076	0.214918	2.433694	8.417958	9.264648	0.002149
Mineral resource scarcity	kg Cu eq	4.879697	4.878561	0.109239	2.238648	4.671111	5.097263	0.001092
Marine eutrophication	kg N eq	0.050101	0.050077	0.00121	2.415277	0.047806	0.052537	1.21E-05
Marine ecotoxicity	kg 1,4-DCB	87.03671	87.00091	1.988109	2.284219	83.2761	91.03089	0.019881
Land use	m2a crop eq	37.98247	37.97033	0.846307	2.228152	36.38179	39.68417	0.008463
Ionizing radiation	kBq Co-60 eq	89.4259	89.39351	2.128347	2.380012	85.33504	93.6551	0.021283
Human non-carcinogenic toxicity	kg 1,4-DCB	1519.267	1518.643	36.09376	2.375735	1450.605	1591.595	0.360938
Human carcinogenic toxicity	kg 1,4-DCB	129.211	129.1511	2.94952	2.282715	123.5767	135.1407	0.029495
Global warming	kg CO2 eq	3182.164	3180.662	73.50303	2.309844	3041.712	3329.843	0.73503
Freshwater eutrophication	kg P eq	0.607856	0.607458	0.016153	2.657442	0.577224	0.640222	0.000162
Freshwater ecotoxicity	kg 1,4-DCB	64.94227	64.91881	1.490697	2.295418	62.10834	67.93512	0.014907
Fossil resource scarcity	kg oil eq	1879.794	1879.226	43.60092	2.319452	1796.685	1966.327	0.436009
Fine particulate matter formation	kg PM2.5 eq	4.137242	4.134871	0.103887	2.511027	3.93745	4.348331	0.001039
SC2								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	526.8139	526.3701	17.45858	3.313994	493.5385	562.3892	0.174586
Terrestrial ecotoxicity	kg 1,4-DCB	7760.617	7757.884	148.9248	1.918981	7474.12	8057.723	1.489248
Terrestrial acidification	kg SO2 eq	16.16331	16.16109	0.375317	2.322032	15.43571	16.91589	0.003753

Stratospheric ozone depletion	kg CFC11 eq	0.005255	0.00525	0.000163	3.102165	0.004944	0.005588	1.63E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	13.08893	13.0862	0.297959	2.276424	12.50981	13.69333	0.00298
Ozone formation, Human health	kg NOx eq	12.17363	12.17043	0.281387	2.311445	11.62566	12.74299	0.002814
Mineral resource scarcity	kg Cu eq	5.518571	5.517691	0.108715	1.969987	5.311613	5.732302	0.001087
Marine eutrophication	kg N eq	1.310744	1.309605	0.042821	3.266906	1.228798	1.39809	0.000428
Marine ecotoxicity	kg 1,4-DCB	76.43099	76.42203	1.450679	1.898025	73.63765	79.25715	0.014507
Land use	m2a crop eq	757.2051	756.5671	24.60246	3.249115	710.3067	807.4682	0.246025
Ionizing radiation	kBq Co-60 eq	55.8904	55.89335	1.120161	2.00421	53.71674	58.06355	0.011202
Human non-carcinogenic toxicity	kg 1,4-DCB	1285.121	1284.678	27.16472	2.113786	1232.982	1338.538	0.271647
Human carcinogenic toxicity	kg 1,4-DCB	178.7233	178.68	3.886387	2.174528	171.2048	186.4689	0.038864
Global warming	kg CO2 eq	2920.973	2920.733	57.734	1.976533	2810.181	3034.363	0.57734
Freshwater eutrophication	kg P eq	0.447995	0.447517	0.012529	2.796788	0.424777	0.473704	0.000125
Freshwater ecotoxicity	kg 1,4-DCB	54.07199	54.06694	1.022606	1.891193	52.10513	56.05436	0.010226
Fossil resource scarcity	kg oil eq	2576.522	2575.794	57.19586	2.219886	2466.247	2689.554	0.571959
Fine particulate matter formation	kg PM2.5 eq	5.660712	5.660483	0.128192	2.264583	5.412368	5.916533	0.001282
SC3								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	5.593998	5.593268	0.129667	2.317958	5.343799	5.854019	0.001297
Terrestrial ecotoxicity	kg 1,4-DCB	4145.88	4145.24	81.86259	1.974553	3987.992	4310.702	0.818626
Terrestrial acidification	kg SO2 eq	8.019126	8.011697	0.23751	2.961791	7.570082	8.509949	0.002375
Stratospheric ozone depletion	kg CFC11 eq	0.000415	0.000415	1.11E-05	2.681558	0.000394	0.000438	1.11E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.516369	6.512146	0.167746	2.574225	6.198765	6.857495	0.001677
Ozone formation, Human health	kg NOx eq	6.246728	6.241631	0.163643	2.619663	5.937322	6.579653	0.001636
Mineral resource scarcity	kg Cu eq	2.865084	2.865042	0.059767	2.086053	2.749141	2.985433	0.000598

Marine eutrophication	kg N eq	0.032898	0.032876	0.0009	2.734357	0.031199	0.034709	9.00E-06
Marine ecotoxicity	kg 1,4-DCB	51.56186	51.55378	1.158912	2.247616	49.34176	53.87804	0.011589
Land use	m2a crop eq	27.95263	27.92121	0.825303	2.952505	26.38645	29.66473	0.008253
Ionizing radiation	kBq Co-60 eq	60.4529	60.38999	1.912164	3.163064	56.87938	64.50259	0.019122
Human non-carcinogenic toxicity	kg 1,4-DCB	937.4562	936.981	24.19762	2.5812	891.4145	985.7692	0.241976
Human carcinogenic toxicity	kg 1,4-DCB	78.97683	78.95678	1.843296	2.33397	75.43693	82.66652	0.018433
Global warming	kg CO2 eq	1986.604	1985.839	48.31335	2.431957	1894.091	2083.302	0.483133
Freshwater eutrophication	kg P eq	0.394485	0.394071	0.012664	3.210334	0.370529	0.420156	0.000127
Freshwater ecotoxicity	kg 1,4-DCB	38.19146	38.18436	0.861452	2.255614	36.53054	39.91493	0.008615
Fossil resource scarcity	kg oil eq	1045.127	1044.968	23.02039	2.202641	1000.689	1090.127	0.230204
Fine particulate matter formation	kg PM2.5 eq	2.896052	2.893842	0.08264	2.853529	2.740029	3.065282	0.000826
SC4								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	9.637179	9.63575	0.228829	2.374435	9.19166	10.08865	0.002288
Terrestrial ecotoxicity	kg 1,4-DCB	5915.958	5914.746	135.3224	2.287413	5654.342	6182.827	1.353224
Terrestrial acidification	kg SO2 eq	8.3451	8.343123	0.201598	2.415769	7.953553	8.741918	0.002016
Stratospheric ozone depletion	kg CFC11 eq	0.000537	0.000537	1.36E-05	2.539662	0.000511	0.000564	1.36E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.877008	6.875889	0.162529	2.363368	6.561813	7.197768	0.001625
Ozone formation, Human health	kg NOx eq	6.431891	6.430802	0.152299	2.367878	6.136351	6.732412	0.001523
Mineral resource scarcity	kg Cu eq	4.725986	4.724733	0.110198	2.331747	4.511781	4.944512	0.001102
Marine eutrophication	kg N eq	0.045203	0.045191	0.001081	2.392095	0.043107	0.047335	1.08E-05
Marine ecotoxicity	kg 1,4-DCB	84.39244	84.36644	1.972793	2.337642	80.54857	88.29595	0.019728
Land use	m2a crop eq	42.48318	42.43491	1.259554	2.96483	40.11115	45.02873	0.012596
Ionizing radiation	kBq Co-60 eq	110.81	110.7127	3.242445	2.926131	104.6596	117.3992	0.032424

Human non-carcinogenic toxicity	kg 1,4-DCB	1409.151	1408.703	32.98051	2.340452	1345.158	1474.572	0.329805
Human carcinogenic toxicity	kg 1,4-DCB	119.9445	119.9134	2.807354	2.340543	114.4885	125.4948	0.028074
Global warming	kg CO2 eq	3042.05	3041.65	72.39838	2.379921	2901.182	3185.16	0.723984
Freshwater eutrophication	kg P eq	0.559229	0.559108	0.013497	2.413572	0.533013	0.585823	0.000135
Freshwater ecotoxicity	kg 1,4-DCB	63.47806	63.46231	1.486168	2.341231	60.59136	66.41736	0.014862
Fossil resource scarcity	kg oil eq	1845.662	1844.884	43.29523	2.345783	1761.517	1931.649	0.432952
Fine particulate matter formation	kg PM2.5 eq	3.18887	3.188377	0.076234	2.390623	3.040978	3.338955	0.000762
SC5								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	527.3959	527.0234	17.5501	3.32769	493.3176	562.8532	0.175501
Terrestrial ecotoxicity	kg 1,4-DCB	7454.981	7453.986	149.9249	2.01107	7164.092	7752.257	1.499249
Terrestrial acidification	kg SO2 eq	14.15104	14.15037	0.341879	2.415925	13.48497	14.83344	0.003419
Stratospheric ozone depletion	kg CFC11 eq	0.005233	0.00523	0.000164	3.132309	0.004916	0.005564	1.64E-06
Ozone formation, Terrestrial ecosystems	kg NOx eq	11.53516	11.53071	0.29151	2.527139	10.97414	12.12549	0.002915
Ozone formation, Human health	kg NOx eq	10.62835	10.62478	0.274096	2.578917	10.10345	11.18434	0.002741
Mineral resource scarcity	kg Cu eq	5.49452	5.493488	0.112316	2.044138	5.278585	5.716239	0.001123
Marine eutrophication	kg N eq	1.307865	1.307009	0.04304	3.290884	1.224455	1.394596	0.00043
Marine ecotoxicity	kg 1,4-DCB	75.02334	75.00087	1.466699	1.95499	72.23408	77.95491	0.014667
Land use	m2a crop eq	763.243	762.725	24.74364	3.241909	715.3318	813.1888	0.247436
Ionizing radiation	kBq Co-60 eq	77.69128	77.57253	2.736385	3.522127	72.70515	83.32419	0.027364
Human non-carcinogenic toxicity	kg 1,4-DCB	1194.79	1194.387	23.5643	1.972255	1149.796	1241.886	0.235643
Human carcinogenic toxicity	kg 1,4-DCB	172.2499	172.1945	3.833876	2.225765	164.8294	179.934	0.038339
Global warming	kg CO2 eq	2841.77	2840.702	58.11221	2.04493	2731.495	2958.229	0.581122
Freshwater eutrophication	kg P eq	0.402898	0.40261	0.009188	2.280397	0.385739	0.421589	9.19E-05

Freshwater ecotoxicity	kg 1,4-DCB	53.38624	53.36703	1.04413	1.955804	51.38967	55.46741	0.010441
Fossil resource scarcity	kg oil eq	2561.072	2560.355	57.56822	2.247818	2449.989	2675.883	0.575682
Fine particulate matter formation	kg PM2.5 eq	4.985262	4.984771	0.116424	2.335367	4.758337	5.218194	0.001164
SC6								
Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Water consumption	m3	5.789042	5.787657	0.15089	2.60647	5.500713	6.087034	0.001509
Terrestrial ecotoxicity	kg 1,4-DCB	3479.384	3478.24	81.11164	2.331207	3322.179	3640.564	0.811116
Terrestrial acidification	kg SO2 eq	5.178466	5.175927	0.143387	2.768918	4.902219	5.461709	0.001434
Stratospheric ozone depletion	kg CFC11 eq	0.000362	0.000362	1.14E-05	3.14819	0.00034	0.000385	1.14E-07
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.097076	4.096142	0.104925	2.560966	3.896976	4.3038	0.001049
Ozone formation, Human health	kg NOx eq	3.849627	3.84852	0.099408	2.582274	3.660036	4.045147	0.000994
Mineral resource scarcity	kg Cu eq	2.712664	2.712306	0.064733	2.386309	2.588099	2.839552	0.000647
Marine eutrophication	kg N eq	0.028015	0.028006	0.00076	2.711472	0.026554	0.029515	7.60E-06
Marine ecotoxicity	kg 1,4-DCB	48.94454	48.93685	1.190282	2.4319	46.6611	51.27494	0.011903
Land use	m2a crop eq	32.45245	32.41531	1.262782	3.891175	30.07842	35.01431	0.012628
Ionizing radiation	kBq Co-60 eq	81.82918	81.73287	3.138691	3.835662	75.92421	88.21493	0.031387
Human non-carcinogenic toxicity	kg 1,4-DCB	827.8803	827.69	20.44175	2.469168	788.911	867.9232	0.204418
Human carcinogenic toxicity	kg 1,4-DCB	69.75164	69.73464	1.704466	2.443621	66.49252	73.1158	0.017045
Global warming	kg CO2 eq	1847.387	1846.934	48.81443	2.64235	1753.549	1943.751	0.488144
Freshwater eutrophication	kg P eq	0.346077	0.34593	0.009548	2.758851	0.327682	0.364908	9.55E-05
Freshwater ecotoxicity	kg 1,4-DCB	36.74722	36.73949	0.895841	2.437847	35.02717	38.50565	0.008958
Fossil resource scarcity	kg oil eq	1011.614	1011.558	23.64803	2.337654	965.8238	1058.299	0.23648
Fine particulate matter formation	kg PM2.5 eq	1.94888	1.948371	0.052246	2.680847	1.848141	2.052112	0.000522

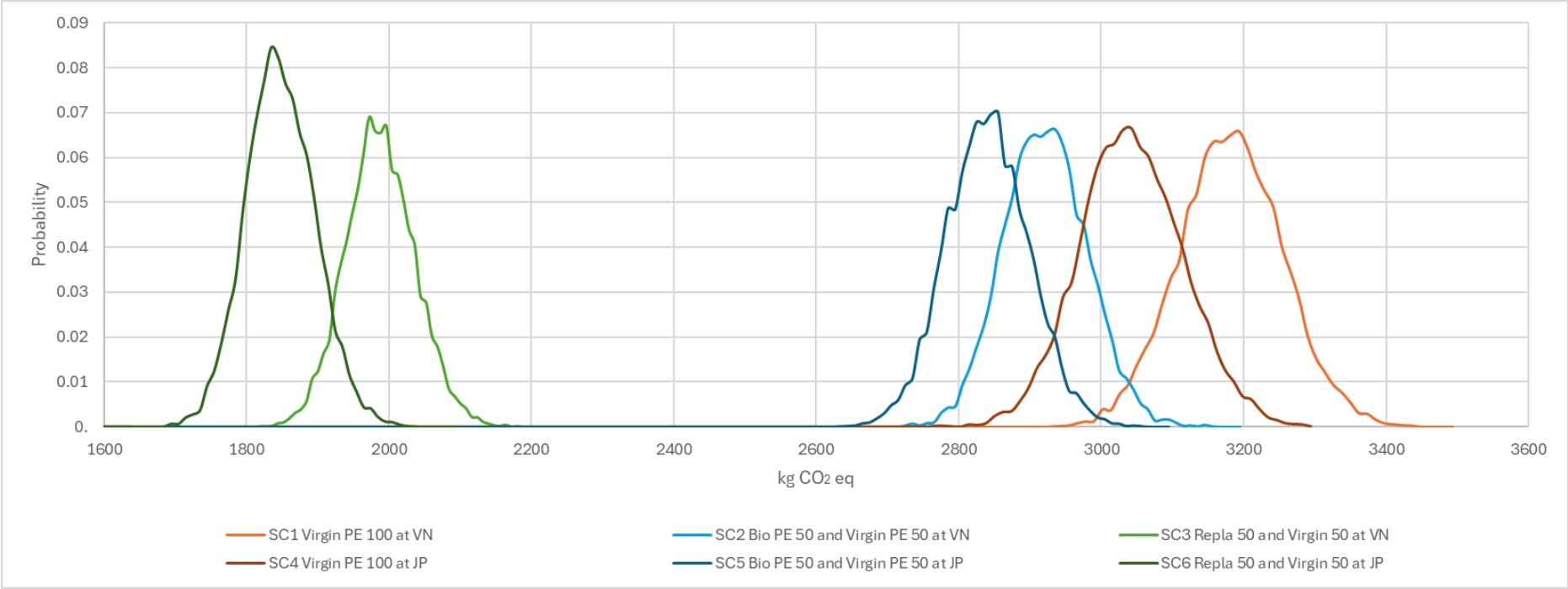


Figure S2: Monte Carlo simulation results – distributions across all scenarios

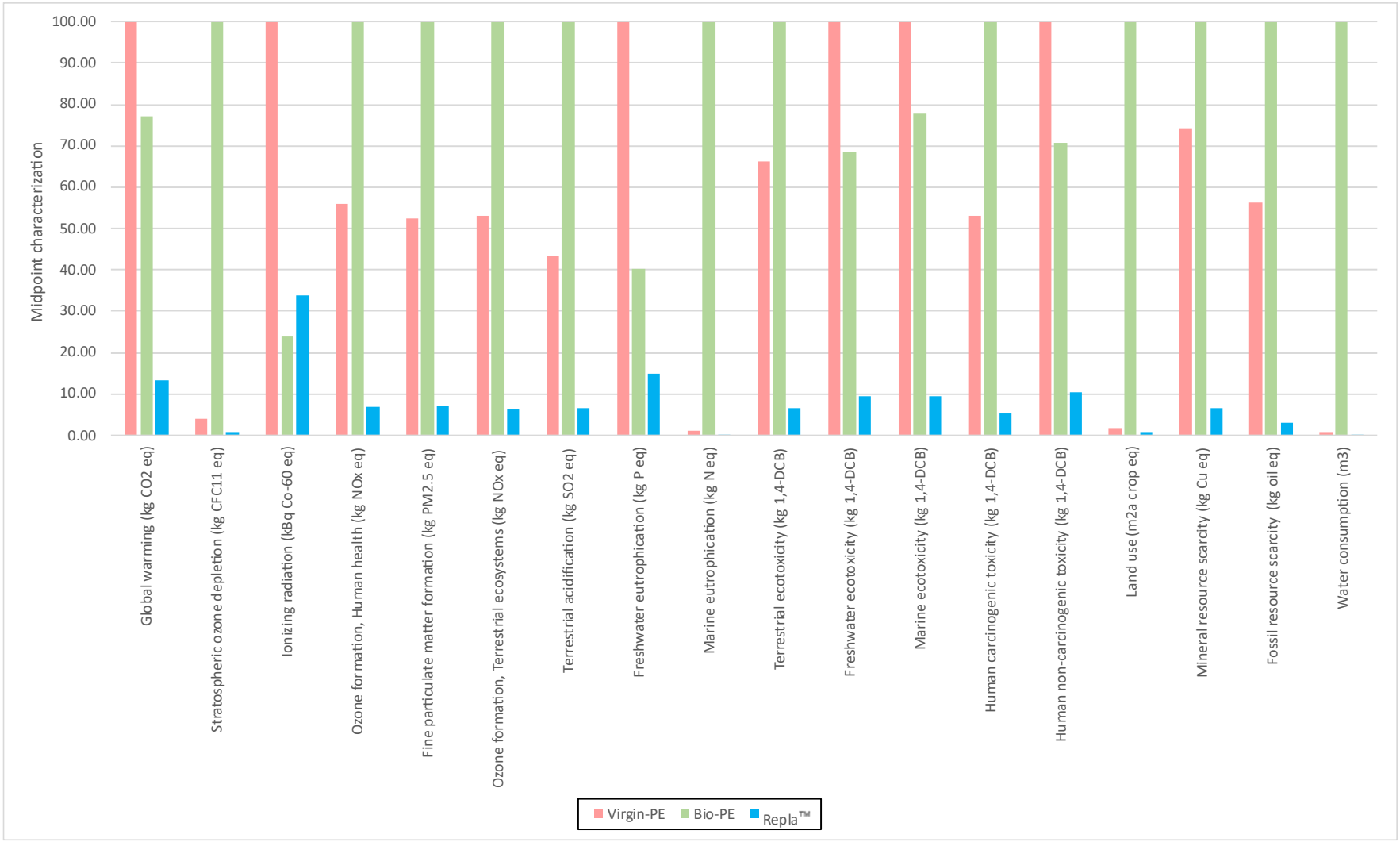


Figure S3: Midpoint Characterization Comparisons of Plastic Pellets (which is same with Figure 3 of the main text)

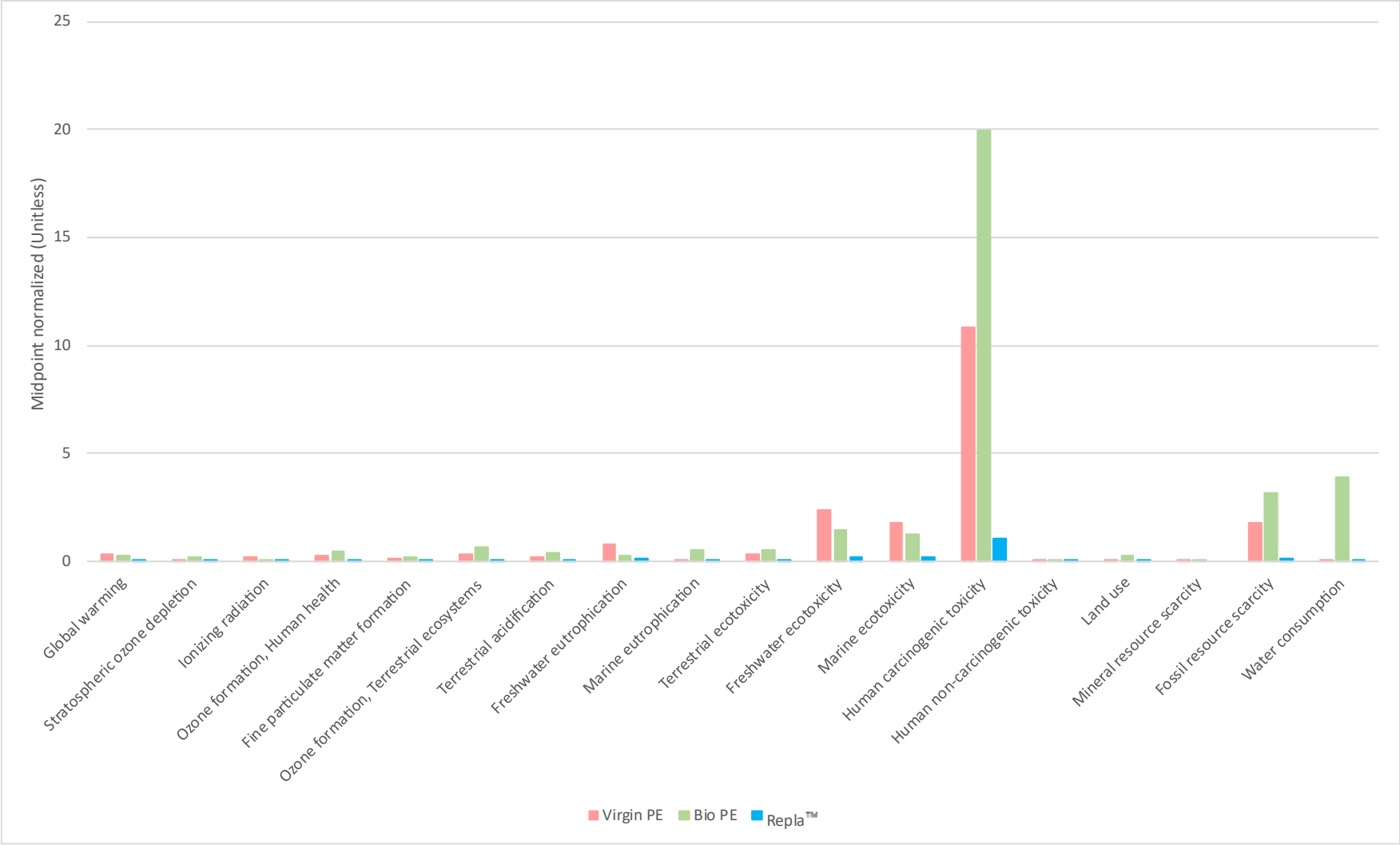


Figure S4: Midpoint Normalized Comparison of Plastic Pellets

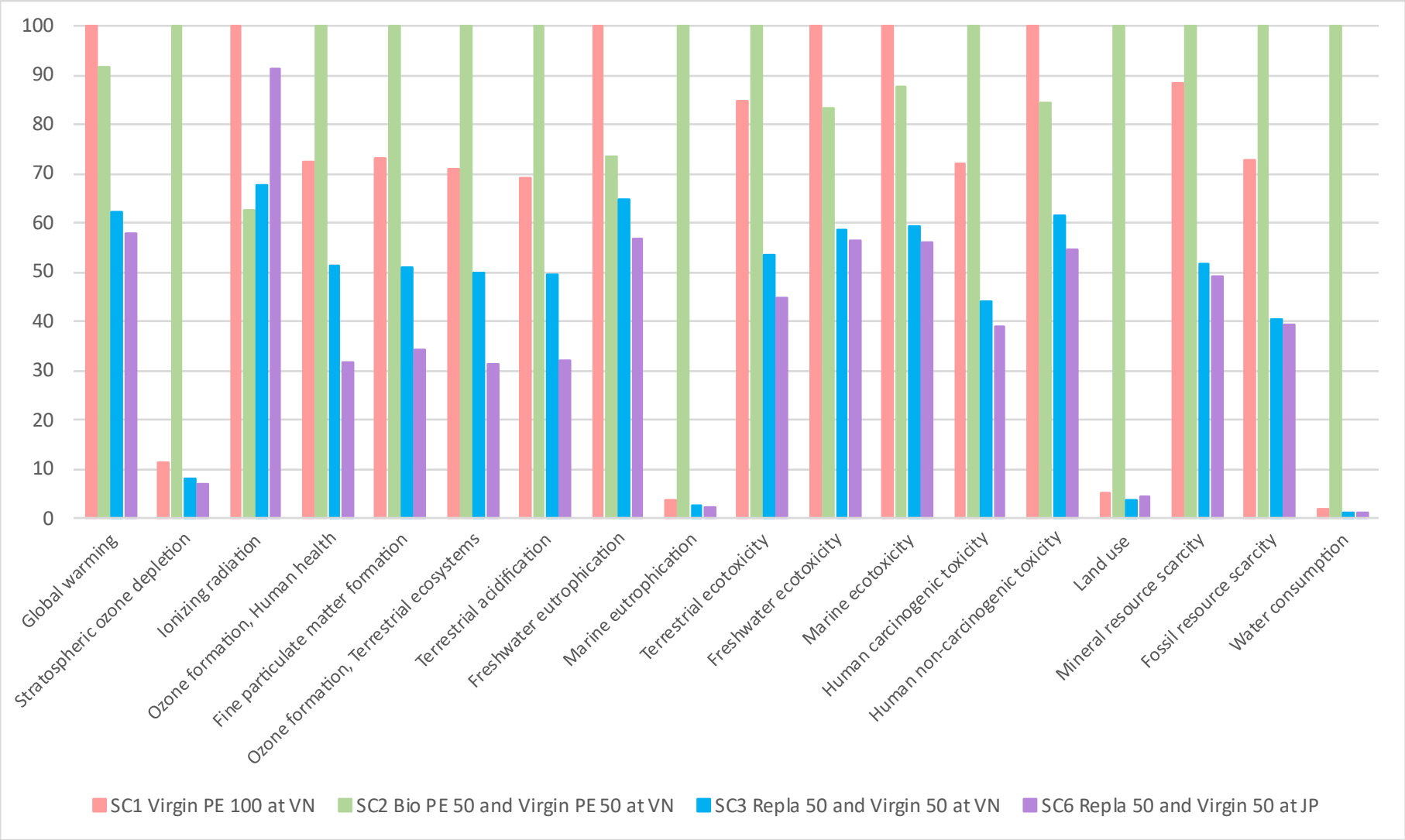


Figure S5: Midpoint Characterization Comparison of Plastic Bag Production Scenarios

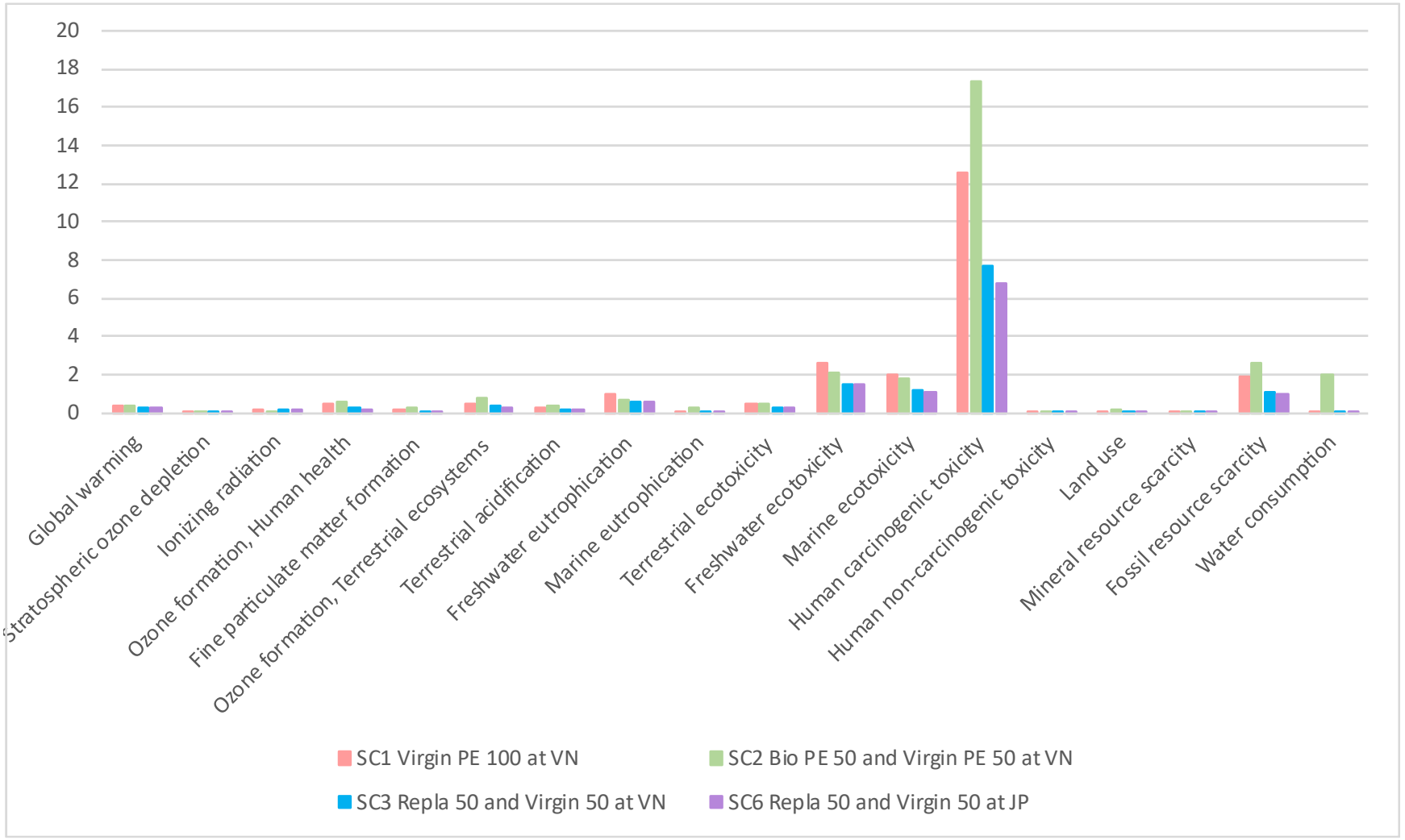


Figure S6: Midpoint Normalized Comparison of Plastic Bag Production