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Nomographs for Polymeric Material Selection for Environmental Conscious Design of Industrial Products

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ABSTRACT

Environmentally-conscious product design using Life Cycle Assessment (LCA) deserves the utmost attention to save and sustain our planet's lives, flora and fauna. The choice of materials during the design stage needs to address environmental concerns from their sourcing to production and ultimately going up to the disposal stage. A good majority of industrial products are still not designed, focusing the environmental concerns. The inclusion and practice of the LCA approach during product designing are in a nascent stage not only in India but even over the rest of the world. Nowadays, polymers share a major chunk of the volume of goods produced worldwide and thus have a significant effect on the environment. The available design books or nomographs guide the selection of materials considering several criteria but not considering the related environmental issues. This paper attempts to bridge this gap only for the selection of polymeric materials by providing some easily interpretable and visually ready reckoners in the form of 3-D nomographs. These 3-D nomographs, graphical representations developed using the Solidworks software, echo the material's Environmental Impact (EI) potential on an axis with some two material properties (e.g., tensile strength and density) on the other two axes. 3-D nomographs are suitably transformed into 2-D nomographs without the loss of any information. EIs on these nomographs were computed using SimaPro software. The potential EI of any product and the overall environmental burden due to them can be significantly reduced, and more so when they are mass-produced, by selecting the right materials using these nomographs. Such an approach will help in fulfilling long-term sustainable development goals of society and the globe.

Keywords: Nomographs; Polymers; Material selection; Product design

NOMENCLATURE

ABS	:	Acrylonitrile Butadiene Styrene
EVA	:	Ethylene Vinyl Acetate
HDPE	:	High-Density Polyethylene
HIPS	:	High-Impact Polystyrene
LLDPE	:	Linear Low-Density Polyethylene
Ny6-6	:	Polyamide/Nylon 6-6
Ny-6	:	Polyamide/ Nylon 6
PC	:	Polycarbonate
PET	:	Polyethylene Terephthalate
PLA	:	Polylactic Acid /Polylactide
PMMA	:	Polymethyl Methacrylate
PP	:	Polypropylene
PPS	:	Polyphenylene Sulfide
PTFE	:	Polytetrafluoroethylene
PVC	:	Poly Vinyl Chloride

1. INTRODUCTION

Product development or service rendering always has some amount of environmental impact (EI), affecting nature and the ecosystems negatively. Even though the impact cannot be zeroed down, its level can be minimized by adopting appropriate scientific strategies. It will cause the development process to be sustainable. According to Ashby[1], sustainable development should find the new state more sustainable compared to the present state. This to happen will naturally call for the quantification of EI. Quantitative evaluation of the environmental impact of any product or service throughout its life cycle (i.e., from raw material extraction, production, use and finally to disposal) has been termed Life Cycle Assessment (LCA)[2]. LCA studies, to be carried out during the product design stage, can help in knowing the potential EI of any product or service well in advance. Product design with environmental considerations is often referred to as Environmental Conscious Design (ECD). ECD using LCA is the need of the hour to save our planet's lives, flora and fauna. The use and application of the LCA concepts for the design of industrial products are in a very nascent stage the world over. Although efforts are being made worldwide to bring the LCA concept to the product design, it is still not very popular and common due to the following reasons.

- Lack of awareness and subject knowledge of LCA and ECD
- Lack of knowledge about the potential benefits of ECD

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amongst Governments, policymakers and industries
- Most importantly, lack of ready-reckoner for designers to easily assimilate and apply the LCA concepts during the design stage.

Industrial products and consumer goods, particularly bulk-used ones, provide a big scope and opportunity to reduce the associated environmental and health impact. ECD is a less addressed area. Material scientists and design engineers can contribute significantly, provided they receive guidance on the material selection associated with their EI. The information to be provided should be easy to interpret and work with. From this perspective of helping the designers, an effort has been made in this paper to present certain nomographs to be used for selecting one from a host of polymers.

Polymers find their ever-increasing share in the volume of goods produced worldwide because these offer some distinct advantages over metals. Polymers are lightweight with high ductility, high flexibility, and high impact strength. They are preferred over metals because of their easy processing, less consumption of energy in manufacturing, corrosion-free performance, transparency, etc. The advanced grades of these polymers and composites possess strength very much comparable to metals. Due to these advantageous qualities, polymers find their applications almost in all the fields of engineering. Their growing applications are also being witnessed in defence and aerospace. Based on the work carried out by Ashby[1], Fig. 1 is drawn which shows the volume of annual usage of some polymeric and metallic materials. The large use of polymers is notable, and their production volume is more than the other metal alloys except that of steel.

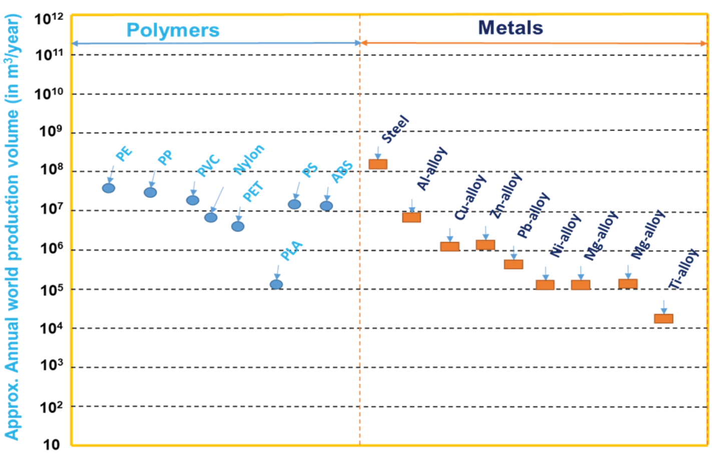


Figure 1. World production volume per year of select industrial materials on the log scale.

Polymers used in significantly large quantities are responsible for growing concern about their usage due to their detrimental impact on the environment. A glimpse of the same can be had from the elaborations to follow next.

Dupont, a global leader in polymer manufacturing, conducts research for analysing the environmental aspects associated with a product to identify improvement areas in materials and processes, to conduct design modification based on the analyses for optimum use, and also to minimize global warming potential[3]. Huang[4], *et al.* have suggested looking into the product's environmental performance right from the designing stage, much before the product enters the manufacturing stage.

The EI of a product is always directly correlated with the environmental attributes of the materials used. EI is witnessed right from material extraction to its processing, product manufacturing, use, and end-of-life. Energy and other resources required at these stages also negatively impact the environment. Therefore, material selection becomes vital in fixing the environmental burden of the products. Jiang[5], *et al.* carried out a detailed review of sustainability in product design. They found a dearth of relevant research on making products more sustainable. They also observed not much utilization of previously published sustainability research in actual product design activities. Ramesh[6], *et al.* conducted a thorough review of the LCA of polymers, and Tabone[7], *et al.* worked on their green designs. It is worth mentioning that none of these researches provides any visual tool to designers in material selection for minimizing the overall environmental impact.

Mustafa[8], *et al.* developed an alternative eco-friendly material in designing non-asbestos brake pads for automobiles. Their experiments found Kenaf fibre to serve as a suitable alternative friction material that not only qualifies all the design requirements but consumes less processing energy compared to asbestos and other potential alternate materials. They carried out the material selection task by using Cambridge Engineering Selector (CES) software and the Eco-Audit tool.

Abdelkareem[9], *et al.* reviewed the environmental aspects of fuel cells (FCs) and found them to have significant environmental improvements compared to conventional energy sources during their use phase while having almost similar performance over their total life. It is because of the comparatively higher environmental impact encountered during material acquisition and manufacturing.

According to Moustafa[10], *et al.* the researchers are also showing great interest in biopolymers because they are 100% biodegradable and have UV light protection. They mentioned eco-friendly synthetic polymer (PLA, PVA, PBAT, etc.) based nano-reinforced composites to be useful for smart food packaging, etc. Waste of such materials was reported to be suitable for industrial composting.

Growing concern towards sustainability is motivating material scientists and design engineers worldwide to care for the environment and enhancement while developing a more sustainable product. Thus, the environmentally conscious design approach must aim to yield a product whose aggregate environmental impact across the life cycle is as small as possible without compromising on quality, cost, performance, and production feasibility.

The materials (polymers or metals) selected during the product design stage are required to possess some key physical/mechanical/thermal properties (such as strength, toughness, modulus, etc.) to fulfil the primary design requirements besides meeting functional requirements (such as sustaining extremely low or high service temperature, etc.). These specific properties set the qualifying criteria for selecting a competent material for the specific application of the product. Many design engineers use Ashby's charts, 2-D charts developed by

Ashby[1], for material selection. These charts take care of the physical, mechanical and thermal properties of the material but do not guide the material selection based on environmental considerations. By including environmental impact on the third axis, added to these 2-D charts, a designer can view the impact on the environment due to the material being selected. Using these charts, one can minimize the environmental impact of the product by selecting the appropriate material.

The charts developed in this paper are only for a few polymers. These show the environmental impact (on a cradle-to-gate basis) versus some other two material properties. These charts will help in deciding the right polymer for specific engineering applications while minimizing the environmental burden.

2. POLYMERS CONSIDERED AND THEIR ENVIRONMENTAL IMPACT

The most commonly used polymers in producing the products are ABS, HDPE, HIPS, LLDPE, Nylon 6-6, Nylon 6, PC, PET, PPS and PMMA. Some special grades of commodity plastics, such as EVA, PP and PVC, also find their applications in many products. PLA is a natural-fibre and biodegradable polymer, and it might potentially replace some of the above-mentioned polymers as a greener substitute with equivalence in other performance criteria. LCA and EI data are precisely available for all these materials and thus are considered in the present work of nomographs' development. The property data of the above-mentioned industrial-grade polymeric materials are shown in Table 1, along with some particular grades of these materials that find their use in mass-produced industrial products.

For drawing the nomographs, mechanical and thermal properties of concern and importance are taken. Material properties considered are also listed in Table 1. These are tensile strength, density, toughness or impact strength, tensile modulus, hardness, maximum continuous service temperature, minimum continuous service temperature, or ductile-brittle transition temperature. The current purchase price applicable in India is also listed for help in evaluating alternate designs based on economic considerations.

For selecting a material for a particular application, two key properties are generally identified as necessary to fulfil the primary design criteria of the product. For some varied applications, the design criteria adopted and the corresponding key material properties are listed in Table 2.

Quantitative evaluation of the EI of these materials has been carried out using SimaPro software[18] version 9.2.0.2, which is meant for carrying out LCA. This software is mainly based on ISO 14040[1] (Life Cycle Assessment - Principles and Framework), ISO 14044[19] (Life Cycle Assessment - Requirements and Guideline) and LCA best practices listed in ILCD[20] **(**The International Reference Life Cycle Data System**)** Handbook. SimaPro software uses the Ecoinvent[21-22] database (developed by a not-for-profit association based in Zurich, Switzerland) with high-quality data for sustainability assessments. Various standard methods are available in SimaPro for systematically performing impact category selection, characterization and life cycle impact assessment. Its ReCiPe[23-24] 2016 Endpoint (H) V1.05 method is chosen and used for EI computation.

The EIs in SimaPro are expressed by two kinds of category indicators: midpoint and endpoint. The midpoint impact category indicator shows the impact on each of the eighteen environmental issues in number in the ReCiPe method. These are global warming, ozone layer depletion, ionizing radiation, ozone formation, fine particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial eco-toxicity, freshwater eco-toxicity, marine eco-toxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity and water consumption. The

Table 1. Material property data[11-17]

Material	Tensile strength (in MPa)	Tensile modulus (in GPa)	Density (in g/cm^3)	Notched Izod impact strength at 23 °C (in J/m^2)	Hardness (Shore D values)	Max. continuous service temperature (in °C)	Min. continuous service/ Ductile-Brittle transition temperature (in °C)	Price (in INR per kg)
ABS	55	3.2	1.02	215	100	86	40	160
EVA	24	0.20	0.92	999	45	45	69	220
HDPE	27	1.1	0.94	220	70	100	70	120
HIPS	40	3.0	1.03	350	75	60	40	130
LLDPE	45	0.525	0.915	999	56	90	70	95
Ny6-6	86	3.5	1.12	150	95	80	80	250
Ny-6	74	2.0	1.13	160	95	80	40	150
PC	65	2.5	1.2	650	95	100	20	250
PET	58	3.5	1.3	140	95	80	40	103
PLA	50	3.6	1.23	250	75	60	45	350
PMMA	70	3.5	1.17	25	99	70	40	200
PP	35	1.6	0.90	500	85	90	20	106
PPS	80	4.0	1.35	25	100	200	50	600
PTFE	10	0.8	2.10	200	50	260	200	600
PVC	60	4.0	1.35	110	90	50	40	180

Table 2. Design criteria, key material property and applications

Design criteria	Key material properties	Applications
High strength and high modulus	Tensile strength and modulus	Strong and stiff products Bullet-Proof Jacket (BPJ), etc.
High strength and low density	Tensile strength and density	Lightweight aerospace and defence products
High strength and high toughness	Tensile strength and impact strength	Strong and durable product subjected to impact loadings
High strength and high hardness	Tensile strength and shore D hardness	Strong and scratch/ wear resistant products, e.g. Goggle lenses, Automobile body parts
High strength and high temperature	Tensile strength and maximum continuous service temperature	Strong, durable and heat-resistant products
High strength and low temperature	Tensile strength and minimum continuous service temperature	High-altitude and extreme cold weather products
High strength and economic	Tensile strength and price	Durable consumer goods with mass-scale consumption

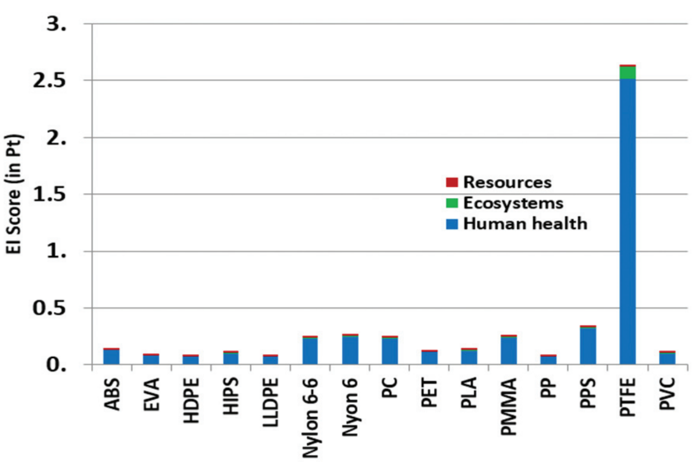


Figure 2. EI as a single score (in Pt.) of some polymers as obtained from SimaPro.

endpoint impact category indicator shows the aggregated effect of midpoint indicators on three more interpretable categories: damage to human health, ecosystem and resource depletion. The used method integrates and implements both midpoint indicators and endpoint impact category indicators[25]. The final EI is expressed in mPt (millipoints) unit, where the Pt (point) is the total environmental burden expressed as a single score. 1 Pt is the average yearly environmental load caused by 1000 European inhabitants.

SimaPro takes 1 kg of a selected polymer as input and then computes inventories (all inputs and outputs in the form of either material and/or energy) required for the production of 1 kg of the selected polymer. Finally, the EIs of these inventories are summed up, and cumulative EI (as a single score in Pt) is determined using SimaPro software on the "cradle to gate" basis for 1 kg usage of the selected material. EIs as a single score for the production of 1 kg of certain polymers (as determined from SimaPro software) are shown in Fig. 2.

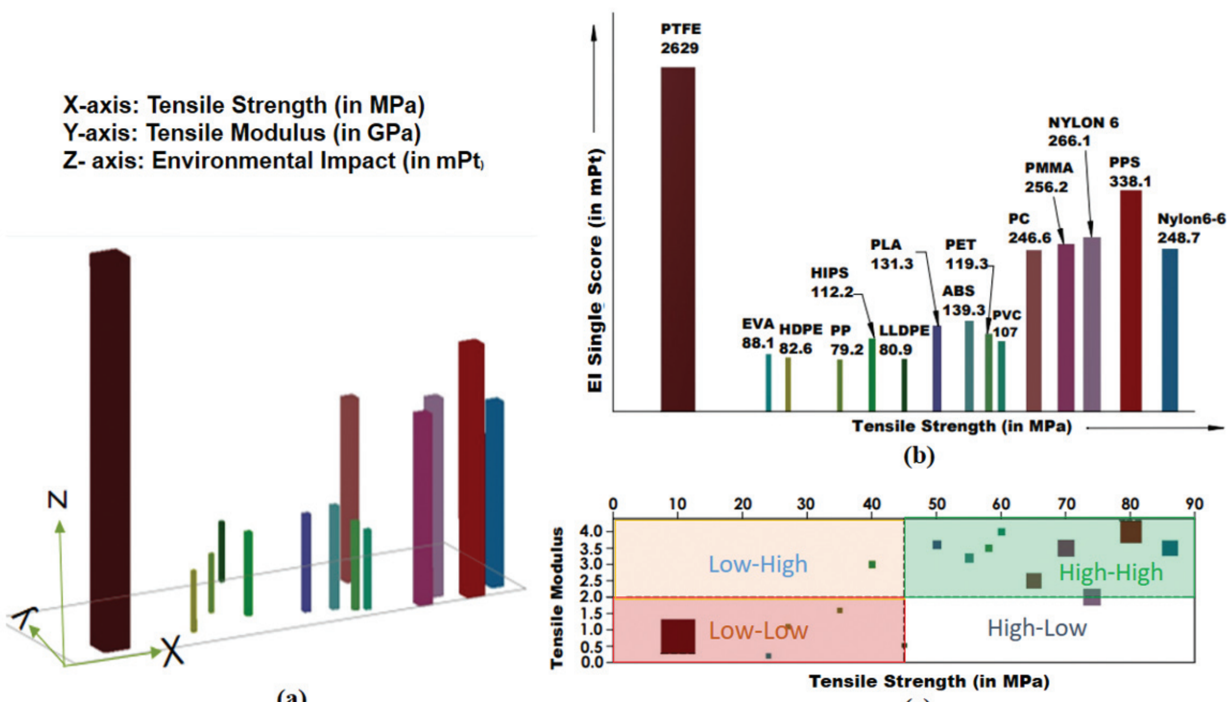


Figure 3. Nomograph-1 relating tensile strength, tensile modulus, and EI single score: (a) 3-D view, (b) Elevation view and (c) Plan view.

3. NOMOGRAPHS DEVELOPED

For easing the task of environmentally conscious material selection based on some two required key mechanical/thermal properties (tensile strength, density, impact strength, strength to density ratio, melting/ softening point temperature, ductile-brittle transition temperature, hardness etc.) for a particular product design, the proposed 3-D graphs/nomographs are prepared using Solidworks software. Nomographs are initially developed as a three-dimensional graph with any two material properties (e.g., tensile strength and density, etc., as listed in Table 2) on two axes and the environmental impact (EI) potential of the material on the third axis. These are made on a true scale and bear an exact 3-D representation of the EI for various selected polymers (Fig. 2).

Figure 3(a) is one such nomograph with tensile strength on the x-axis, tensile modulus on the y-axis, and EI on the z-axis. Both the height and cross-sectional area of each bar in Figure 3(a) are directly proportional to the EI that the material causes. The elevation and plan of the 3-D nomograph are respectively shown in Figs. 3(b) and 3(c). The height of bars in Fig. 3(b) and the size of squares in Fig. 3(c) are in proportion to the EIs that the corresponding polymers cause. Out of these three representations, the style of the nomograph shown in Fig. 3(c) is more user-friendly from the perspective of material selection. Nomograph, shown in Fig. 3(c), can have four quadrangles with the range of tensile strength and the tensile modulus divided into two halves: High and Low. Thus, this nomograph will have four zones: High-High, High-Low, Low-High, and Low-Low. If a designer wishes to have high tensile strength polymer with high tensile modulus, he should look into the High-High zone and select a material having the lowest EI with the smallest size of the square. Zone categorisation and then selecting an appropriate material from the relevant zone eases the work of a design engineer towards ECD. The area of the chart of Fig. 3(c) can be divided into the desired number of parts depending upon the requirements of the design. For example, if the properties on the x-axis and y-axis are categorized as high, medium and low, the chart will then have nine divisions. Depending upon the requirement, the designer can select the appropriate polymer from a zone out of the total nine ones.

The concepts discussed above in designing the nomographs shown in Fig. 3(b) and Fig. 3(c) are used to develop other nomographs, which are shown in Fig. 4 to Fig. 9 for the other design criteria described in Table 2.

3.1 Nomograph-1: Tensile Strength–Tensile Modulus–Environmental Impact

High strength and high modulus polymers find their application either where the load-bearing capability and tight tolerances are required or where metal-to-metal contact damages the surfaces, e.g., seals and bearings. Another application is in bullet-proof jackets where high-velocity penetration resistance is required. For such applications, the nomograph, presented in Figs. 3(b) and 3(c), should be used.

3.2 Nomograph-2: Tensile Strength–Density–Environmental Impact

Low-density material is always a preferred choice in aerospace and defence products where light weight is required. For such applications, the nomograph shown in Fig. 4 can be used.

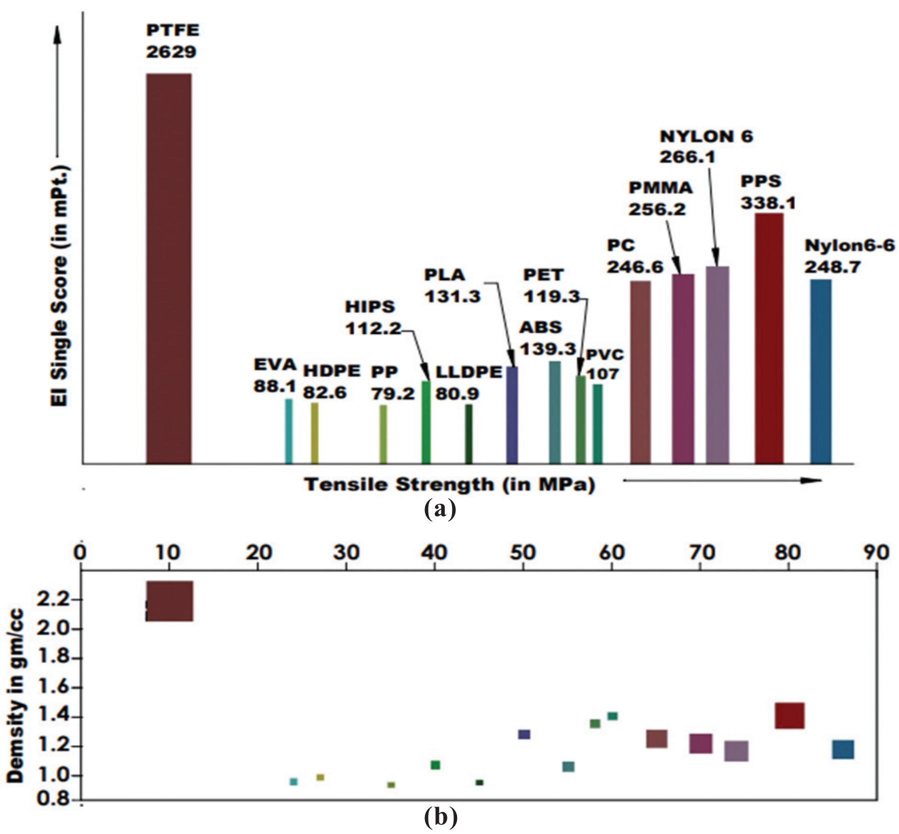


Figure 4. Nomograph-2 relating tensile strength, density and EI single score: (a) Elevation view and (b) Plan view.

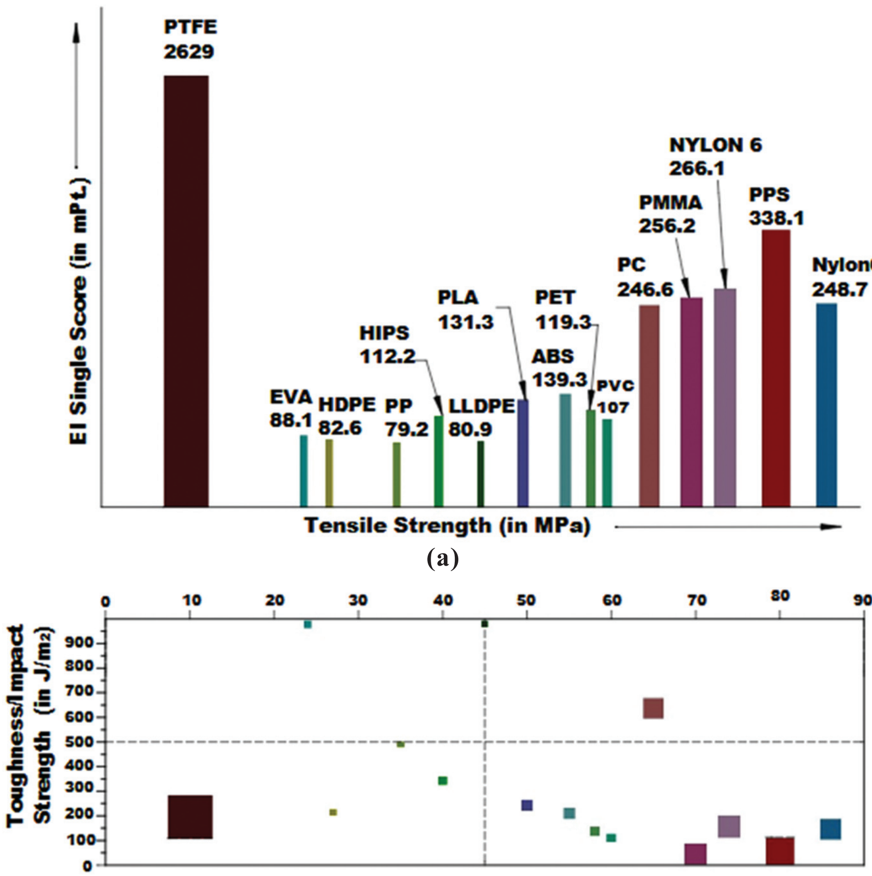


Figure 5. Nomograph-3 relating tensile strength, impact strength and EI single score: (a) Elevation view and (b) Plan view.

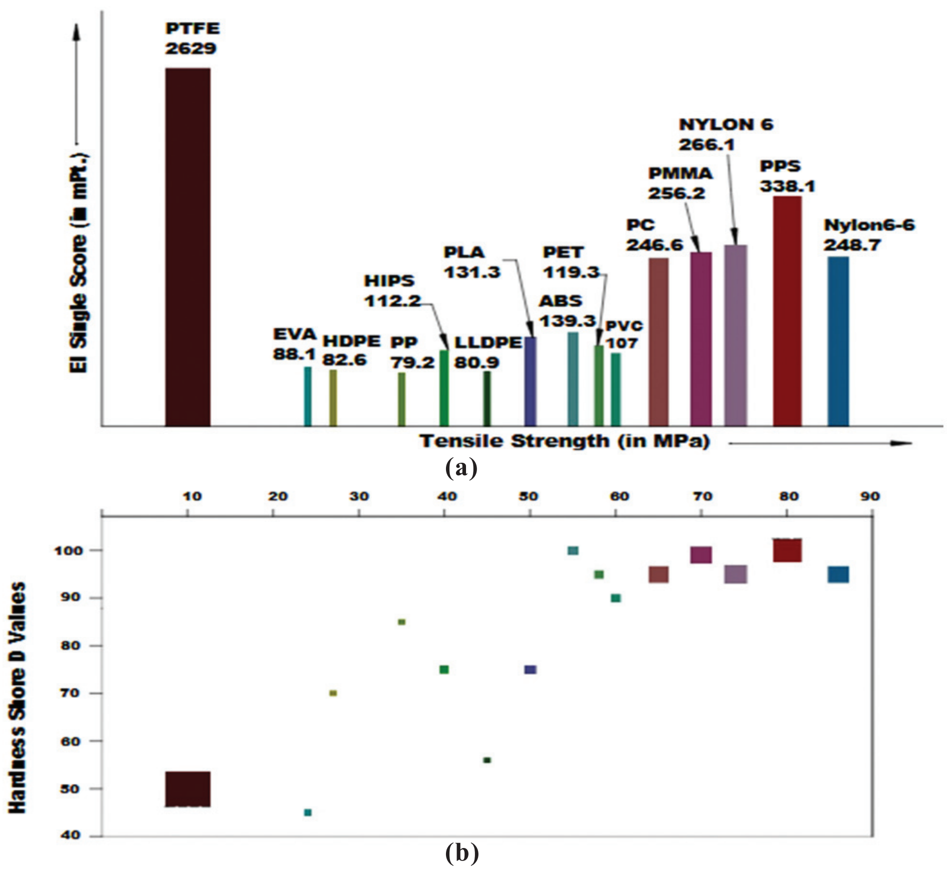


Figure 6. Nomograph-4 relating tensile strength, hardness Shore D and EI single score: (a) Elevation view and (b) Plan view.

3.3 Nomograph-3: Tensile Strength–Impact Strength–Environmental Impact

Products which usually encounter impact or sudden loading require high-impact strength. For the design of defence products that need to qualify for the drop-test, such as water bottles, water and food containers, ration baskets, etc., the nomograph shown in Fig. 5 can be used.

3.4 Nomograph-4: Tensile Strength–Hardness Shore D–Environmental Impact

Hardness is an important property for many aerospace and defence products requiring durable life. Besides, many optical applications require transparency and thus need to have significant hardness to avoid scratches on the related products. In designing such and similar products, the nomograph of Fig. 6 can be used.

3.5 Nomograph-5: Tensile Strength–Maximum Continuous Service Temperature–Environmental Impact

Any product requiring to withstand high temperature or cyclic thermal load (for example, engine O-rings and seals, automobile body, exhaust system components, etc.) will find the nomograph shown in Fig. 7 to be very useful.

3.6 Nomograph-6: Tensile Strength–Minimum Continuous Service Temperature–Environmental Impact

Some polymers lose their ductility and become brittle below certain temperatures. The polymers used for products functioning in extreme cold weather (ECW) conditions are to be assessed by the minimum continuous service temperature or ductile-brittle transition temperature. Selecting polymers for the products that need to function in the ECW environment (for example, ECW goggles. all-terrain defence products besides many used by aerospace industries) may find good use of the nomograph shown in Fig. 8.

3.7 Nomograph-7: Tensile Strength–Price-Environmental Impact

In some cases, the factor of economics cannot be ignored due to the cost-competitiveness prevailing in the world. The purchase price along with any other material property can be taken to plot other nomographs. A sample nomograph of this kind is shown in Fig. 9. This nomograph can be used in the case of those engineering products where the choice of a polymer mostly depends upon the tensile strength.

The concepts presented to draw the nomographs can be used to show EI for other combinations of desired properties

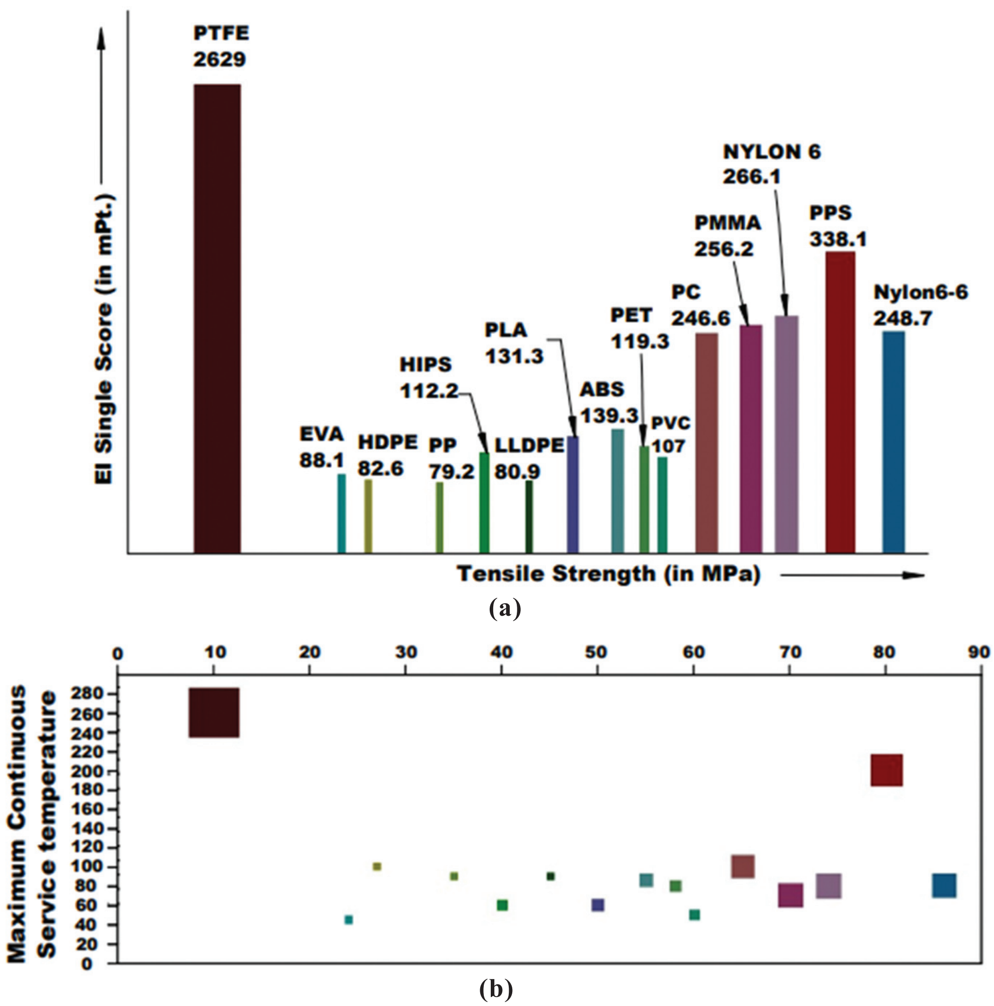


Figure 7. Nomograph-5 relating tensile strength, maximum continuous service temperature and EI single score: (a) Elevation view and (b) Plan view.

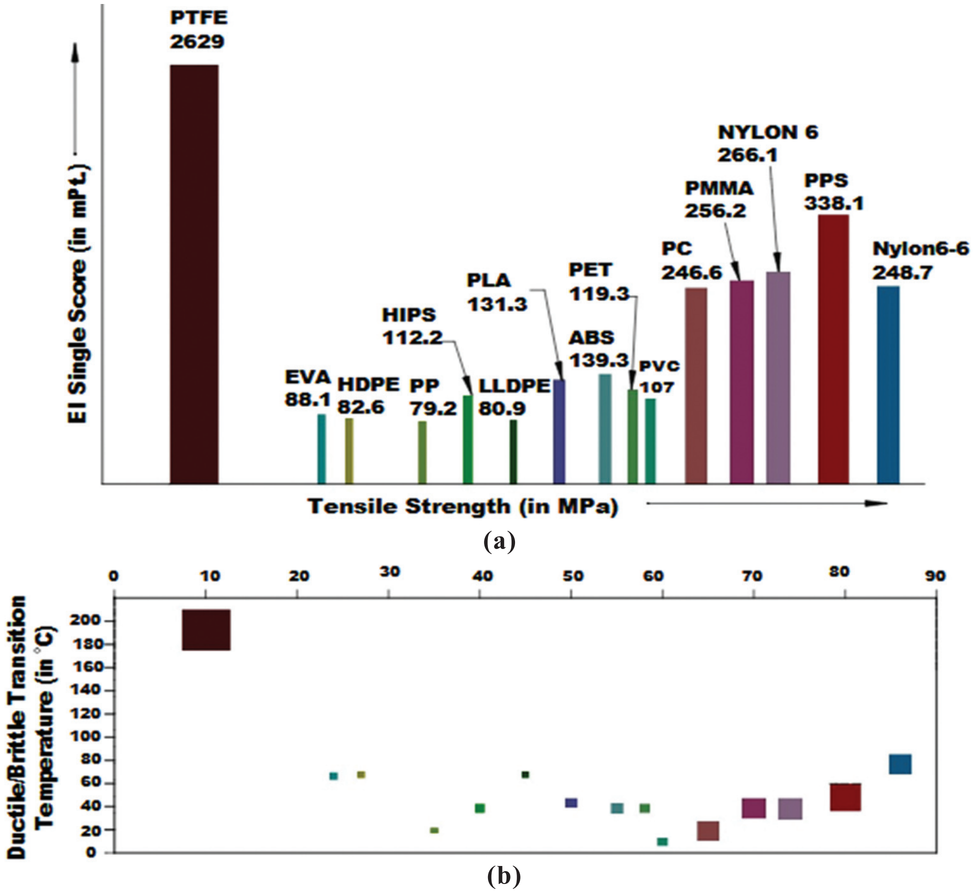


Figure 8. Nomograph-6 relating tensile strength, minimum continuous service temperature and EI single score (a) elevation view (b) plan view.

of the polymer. Depending upon the requirement, one may use more than one nomograph if the polymer to be selected has to cause the lowest EI but has to meet more than two material properties.

4. USING THE DEVELOPED NOMOGRAPHS FOR ECD

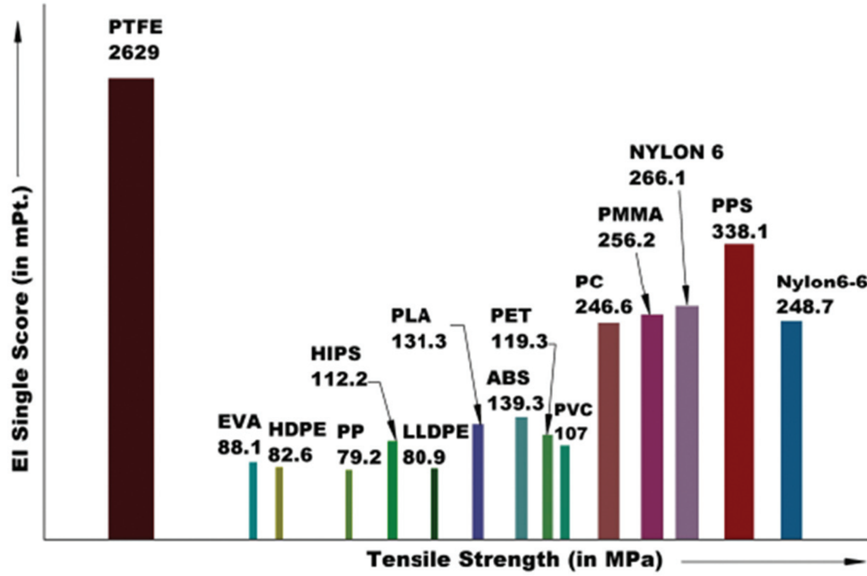
The use of the developed nomographs for material selection is explained by taking a case example. The problem considered is related to the design of a lightweight manual transport system with a minimum tensile strength of 40 MPa. Naturally, the density will be an important property to look into the specified requirement, and thus Nomograph-2 will be the most relevant to use. From the perspective of the required minimum tensile, the nomograph of Fig. 4(b) provides polymer choices on the right side of the 40 MPa tensile strength line. HIPS and LLDPE polymers can be found to meet the technical requirements and also to have low density. LLDPE can be observed to cause low EI compared to HIPS by looking either at the heights of the corresponding bars in Fig. 4(a) or at the size of their corresponding squares shown in Fig. 4(b). Their EI values obtained from Fig. 4(a) are as EI_{HIPS} = 112.2 mPt and EI_{LLDPE} = 80.9 mPt. Out of the two, LLDPE with comparatively lower EI needs to be selected as the best material both from the environmental burden and technical requirement perspectives.

The use of more than one nomograph is illustrated by taking an illustrative example. Say a product is required to be lightweight (density ≤ 1.1 kg/m^3), strong (strength ≥ 30 MPa), and tough against sudden impact (impact strength ≥ 200 J/m^2). In this case, Nomograph-2 and Nomograph-3 are the relevant ones for material selection. Nomograph-2 provides the material choices in the area right to the 30 MPa line and below the 1.1 kg/m^3 line. PP, LLDPE, HIPS and ABS are the possible materials. To take care of the impact strength, Nomograph-3 is to be used. On this nomograph, the area right to the 30 MPa line and above the 200 J/m^2 line finds the material choices as PP, PLA, LLDPE and ABS. The polymers meeting all the three specified requirements are thus PP (EI_{PP} = 79.2 mPt), LLDPE (EI_{LLDPE} = 80.9 mPt) and ABS (EI_{ABS} = 139.3 mPt). Among these, PP is causing the least environmental burden. Therefore, PP emerges as the ECD choice in this case.

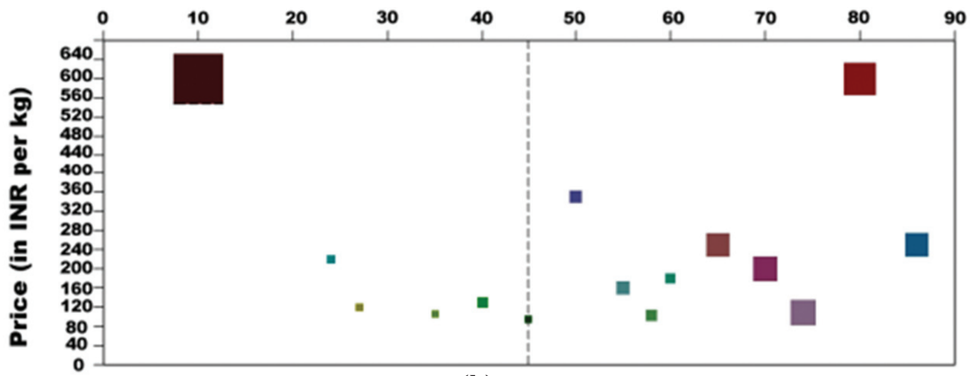
The above illustrations show how the presented nomographs can be used in selecting the right polymer for the specified application and to cause the minimum possible EI. Table 3 illustrates the use of these nomographs in identifying the best ECD polymer by taking hypothetical cases.

5. CONCLUSION

Environmentally conscious design (ECD) is the necessity of time in reducing the environmental burden on the mother earth. The designing stage involves the process of selecting the right material to meet the engineering specifications. Many of the applications desire the use of polymers which have a detrimental impact on the environment. Thus, the right selection



(a)



(b)

Figure 9. Nomograph-7 relating tensile strength, price and EI single score: (a) Elevation view and (b) Plan view.

Table 3. Illustration of the use of nomographs

Application	Key properties	Qualifying polymers	ECD material choices	Best polymer
Strong and stiff product	Strength ≥ 40 MPa and Modulus ≥ 2.0 GPa	PLA, ABS, PET and PVC	PET and PVC	PVC
Strong and lightweight	Strength = 25 MPa Density ≤ 1 Kg/m^3	HDPE, LLDPE and PP	HDPE, LLDPE and PP	PP
High tensile and impact strength	Strength ≥ 38 MPa Impact Strength ≥ 180 J/m^2	HIPS, LLDPE, PLA, ABS and PC	HIPS and LLDPE	LLDPE
Extreme low service temperature	Strength ≥ 40 MPa DBTT ≤ - 40 ^oC	HIPS, LLDPE, PLA, Ny-6, Ny-66, PET, PLA, PMMA, PPS and PVC	HIPS, LLDPE and PVC	LLDPE
Extreme high service temperature	Strength ≥ 25MPa Max Cont. Service Temp. ≥ 100 ^oC	HDPE, PC and PPS	HDPE, PC	HDPE
Durable scratch-resistant and transparent	Strength ≥ 40 MPa Shore D Hardness ≥ 90	PC and PMMA	PC and PMMA	PC
Durable and economic	Strength ≥ 50 MPa Price ≤ 200 INR/kg	ABS, PET, PVC, Ny-6 and PMMA	ABS, PET and PVC	PVC

of a polymer in ECD would need information on the EIs of the relevant polymers. From this perspective, one does not find any easily interpretable and user-friendly visual tools in the available literature. This paper attempts to bridge this gap by providing designers with a ready-reckoner tool in the form of nomographs. These nomographs show any two properties (e.g., tensile strength and density) and the environmental impact (EI) potential of the polymers.

The nomographs presented in this paper are only for some significant polymers considering their massive consumption and recycled use. However, the concepts presented here can also be used to prepare nomographs for other materials as well. The nomograph-based design approach will be helpful to scientists, engineers and industries for the reasons of ease in environmentally conscious selection of material. The use of these LCA-based nomographs will substantially reduce the overall environmental burden without making any compromise either in quality or in the features of the product. As a consequence of all these, the nomographs presented in this paper will be decisive in fulfilling the ultimate goal of sustainable development of any society and nation.

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