A simple model for complex waste recycling scenarios in developing economies

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Abstract

Future uncertainties involved in the current waste management activities in the developing nations have been addressed through determining plastic waste recovery, recycling and landfilling scenarios in two case study countries — Bangladesh and India. In order to discern and comprehend the material in-flow and out-flow of such complex successive plastics recoveries and recyclings, within the closed-loop recycling systems present in these two countries, a simple mathematical model is developed. The model is based on limited published information, on extensive fieldwork in Dhaka, Calcutta and Delhi, and on experimental data. An environmental legislative factor has been included in the model which will allow balancing of the quality of recycled products and the amount of landfilling non-recyclable plastics. The model has the potential to create and predict a sound waste database for these countries. Bangladesh has been chosen as a model developing country for this study. The mathematical model can be used in future decision making processes within the plastics recycling arena of the countries concerned to achieve an environmentally sound and cost effective waste management option. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Recycling of waste materials in developing countries like Bangladesh and India is growing and is driven by economic necessity associated with poverty [1,2]. Recent field surveys in Dhaka (Bangladesh) and in Calcutta and Delhi (India) reveal that successive plastic waste recoveries and recyclings dominate all other types of wastes recycling, and have been in operation since 1960 [3,4]. While only a fraction of the total plastic waste is being recycled in most western countries [5], around 95 and 75% of the plastic wastes appears to be recycled in Bangladesh and India, respectively [3]. However, the quality of the successively recycled products in terms of their (i) physical appearance (ii) polymeric properties (iii) health hazards (for the recyclers and users of such products involved) are in serious question [6,7]. This is due to the total lack of concern and government legislation on environmental and hygiene issues. All these uncertainties have provided the thrusts for the current study. This paper aims to determine the scenarios of successive plastics recoveries and recyclings primarily in terms of their amount recovered/recycled and number of times processed (which represents the quality), along with the trade-off between their “further recycling” and “landfilling” of previously recycled and considerably degraded plastics.

In fact, no systematic study has been done in the past in Bangladesh and India to capture the scenario of plastic recycling, either qualitatively or quantitatively, which would help the government to set up a healthy recycling strategy. In this work, Bangladesh is chosen as the model developing country. This is due to the relatively more confined nature of plastic materials’ flow within the country, for example, (a) imports is the only source of plastics, (b) almost nothing of plastics is exported (which was less than 1% of imported pellets in 1993–1994 [3] and can be counter balanced by plastic packaging imported with overseas shipments), and (c) discarded plastics are recovered/recycled extensively (95%) within a closed-loop recycling system. To create a sound database in the absence of sufficient published

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data, a simple mathematical model is developed based on Haque's [3,7] extensive field surveys in Dhaka and experimental data on the mechanical and rheological properties of high density polyethylene (HDPE) collected from the country's waste streams. The number of model parameters is kept to a minimum, which can be very easily updated if needed. The model is used to predict quantitatively: (i) the future amounts of recovery, (ii) the composition and quality (against number of times processed) of different types of recycled plastics, and (iii) amounts of plastics landfilled per year in the next decade. The model is written using FORTRAN77 programming language. The model and the results obtained for Bangladesh have been compared to some extent with the varying amount and quality of plastics present both in waste streams and at market places of Calcutta and Delhi cities (as observed during fieldwork in 1996 and measured experimentally). Finally it is shown that this simple model can be used in future decision making within the plastics recycling arena of any developing country by just changing the model parameters.

2. Recovery and landfill scenarios in Bangladesh and India

The field survey for Bangladesh shows that, out of 95% of any grade/batch of plastic wastes recovered/recycled in the country, 40% recovery is achieved for recycling in the first year and about 55% is recovered in the second year since that batch is marketed. About 5% of the same batch is lost in the system or is not recyclable and ends up in landfill. In contrast, in the case of India 75% of plastic wastes are recovered/recycled [6] in two successive years. The recovery rates can be estimated as 30% and 45% in the first and second year, respectively, along with the remaining 25% for landfill and others, on the basis of similarity in usage and life-span of new or recycled plastic products' [3]. However, these data are not available to the public or to the government. Based on the survey, the plastics recycling scenario of Bangladesh can be presented schematically by Fig. 1. The number of branches grows in a geometric fashion and it is very difficult to quantify and identify the grades of these plastics (in terms of their "number of times processed", the first virgin pellets being "zero time processed").

3. Model development

Bangladesh has been importing virgin plastics since the mid-1960s and also recycling discarded plastics over the same period [3]. However, import statistics of the country have only been officially recorded since 1990. Fig. 2 shows the import trend of the virgin plastic in the country from 1990 to 1995 and these data have been the only basis on which to model the existing and future waste recycling scenarios of the country. A linear least square fit of the data points in Fig. 2 leads to Eq. (1):

Fig. 1. Closed-loop recycling and landfilling of plastic waste in Bangladesh.
\[ y = 2.08 \, x + 6.23 \] \hspace{1cm} (1)\\

where \( x \) = number of years passed from the base year; \( y \) = imports in the corresponding year \( x \).

Note that imports values increased by 2.4 times over only a 5 year period, although the import data points in 1992–1993 and 1993–1994 are below the linear line. This is probably due to the fall in overall importation as a consequence of the political instability and thus economic depreciation in these years resulting from the fall of the 1990s government, presence of the temporary caretaker government and formation of the new government during 1990–1992. Therefore, the linear line plotted in the Fig. 2 is the best possible line based on the available data.

### 3.1. Useful definitions

Assuming that Eq. (1) represents the pattern of virgin plastics imports in Bangladesh, the recovery and recycling scenarios presented in Fig. 1 can be represented by Fig. 3. The top line represents Eq. (1). The following definitions are useful for better understanding of Fig. 3 and to develop a simple model.

#### 3.1.1. No. of times processed (np)

As shown in Fig. 3, the imported virgin plastic is termed as ‘zero times processed: P-0’ materials (the top line radiating from year \( Y_1 \)). It goes through the first melting/moulding process in year \( Y_1 \) and thus new plastic products are termed ‘once processed: P-1’ materials. According to field survey data, 40% of these once processed products are recovered (P-1: 2nd line from the top) in the next year (\( Y_2 \)) and recycled. These recovered materials (P-1) go through the second melting/moulding process during their reprocessing in year \( Y_2 \), and therefore, the recycled articles now become ‘twice processed: P-2’ products. Forty percent of this ‘P-2’ material is recovered in year \( Y_3 \) (fourth line from top) and is also recycled and marketed in this year as ‘thrice processed: P-3’ product. Also in \( Y_3 \), 55% of the ‘zero times processed’ pellets used in producing new products (P-1) in \( Y_1 \) is recovered in year \( Y_3 \) and therefore termed as ‘once processed’ (third line from top). Therefore, in year \( Y_3 \), there are: one ‘zero times processed’, two ‘once processed’ and one ‘twice processed’ products.

#### 3.1.2. Calculation year \((j)\)

As the materials are imported, recovered and landfilled simultaneously in every ‘1 year time step’, according to the recovery scenario (Fig. 1), each year (or time step) is considered either as a ‘year of imports’, ‘year of recovery’, or ‘year of landfilling’, as appropriate. Therefore, each year is also termed a ‘calculation year’.

#### 3.1.3. Slopes, intercepts, extended data points

Since the import line is assumed to be a straight line, all the recovery lines will be straight but with different slopes and intercepts (in the year the line originated). In general the ‘intercept’ of a line corresponds to the amount of materials imported or recovered/recycled in the year the line originated. Except the intercepts all other points (in the calculation year \( Y_j \), \( Y_{j+1}, \ldots, Y_{j+i} \) on a particular line are referred to as ‘extended data points’ representing the amounts imported or recovered in the following years. The following two equations can be used to generate recovery extended data points for all the lines shown in Fig. 3.

\[ E_{40,j,k} = 0.40S_{m,j-1} \cdot x_{40} + R_{40,j} \] \hspace{1cm} (2)

with \( x_{40} = k - j \), with \( k > j \); where \( E_{40,j,k} \) = recovery extended data point in \( Y_k \) for the line originating in

![Fig. 2. Annual imports of virgin polyethylene (HDPE and LDPE) in Bangladesh [8].](image)
and $R_{40,j}$ is the intercept in the year the line originated, and
\[
E_{55,j+1,\ell} = 0.55S_{m,j-1} x_{55} + R_{55,j+1}
\]  
(3)

with $x_{55} = \ell - (j + 1)$ with $\ell > (j + 1)$; where $E_{55,j+1,\ell}$ is the recovery extended data point in year $Y_j$ for the line originating in $Y_{j+1}$. $R_{55,j+1} =$ intercept in the year the line originated, and $S_{m,j-1} =$ slope of the mother line from which the recovery line is originated.

### 3.2. Model — recovery

Given the import line and the strategy for recovery and recycling (according to the field survey), a general computer program has been developed using FORTRAN 77 language to generate automatically all the recovery lines shown in Fig. 3 (details in [3]). This allows calculation of the ‘intercepts’ and ‘extended data points’ values of all the lines at any year (in the past, present or future). These values are then used to calculate the total amount of materials which was present in the past, or is currently present or which will be present in the system in future.

However, for the implementation of environmental legislative measures to maintain the quality of the recycled plastics and to control the amount of landfilling, it is important to identify the materials present or to be present in the systems with their respective ‘number of times processed’ (Haque [3] presents experimental results correlating the quality of the recycled plastics against the ‘number of times processed’). For this a systematic mathematical approach is required. In this work, all the ‘intercepts’ and ‘extended data points’ values are stored in the computer program in the following manner: the intercept ($= 6.23$ million kg) for the import line is stored as $I_{1...}$ and the extended data points for the import line are stored as $I_{x2...}$, $I_{x3...}$, ..., $I_{xj...}$ for the calculation year $Y_2$, $Y_3$, ..., $Y_j$, respectively. For the recovery lines, the intercepts are given a serial no. ‘$i$’. For example in Fig. 3, the serial no. of the intercepts in $Y_4$ are 1, 2, ..., $i$, etc. The values of the recovery intercepts are stored as $R_{np,j,i}$. Here ‘$j$’ corresponds to the calculation year. Please refer to Haque [3] for details.

The ‘extended data points’ on the line originated in the year $Y_k$ with the ‘intercept’ $R_{np,k,i}$ are stored as $R_{x(np,j,m)}$ for all $j > k$, where ‘$m$’ denotes the serial number of the recovery lines with $m = 1, 2, ..., etc., starting from the second line from the top (Fig. 3), respectively.

### 3.2.1. Number of intercepts and extended data points

At any calculation year $j$, addition of all the intercept and the extended data point values will give the total amount of materials present in the system. To ease the
repetitive calculations using a computer (as there are 55 intercepts in Y10; Fig. 3), it is useful to know the total number of intercepts and extended data points in any calculation year \( j \). It is clear from Fig. 3 that the total number of “recovery intercepts” \( N_j \) at any year \( j \geq 3 \) can be given by:

\[
N_j = N_{j-1} + N_{j-2}
\]

with \( N_1 = 1 \) (refers to import intercept at \( Y_1 \)), \( N_2 = 1 \).

Also, it is clear from Fig. 3 that the total number of extended data points, \( N_x_j \) (for both the import line and recovery lines), at any year \( j \) can be given by:

\[
N_x_j = \sum_{i=1}^{j-1} N_i \quad \text{[where]} \quad j \geq 2; \quad \text{with} \quad N_x_1 = 0
\]

Material present in the recycling system at any year: The amount of \( np \) times processed (for \( np > 0 \)) material present in the recycling system at any year \( j \), \( T(np,j) \), is given by:

\[
T(np,j) = \sum_{i=1}^{N_j} R(np,j,i) + \sum_{m=1}^{N_x_j-1} R_x(np,j,m), \quad [j \geq 3]
\]

The total amount of material present in the recycling system at any year \( j \), \( T(j) \) is given by:

\[
T(j) = I(j) + I_x(j) + \sum_{np=0}^{NP} T(np,j), \quad [j \geq 3]
\]

where \( NP \) = maximum value of process number.

3.3. Model — landfilling

According to the landfilling scenario (Fig. 1), 2% of the imports (6.23 million kg) in \( Y_1 \) is discarded and landfilled in \( Y_2 \). A further 3% of the imports in \( Y_1 \) is discarded and landfilled in \( Y_3 \). In general, the landfills are 2% in year \( (j + 1) \) and 3% in year \( (j + 2) \) of the materials recovered and recycled in year \( j \) (as represented by the intercepts or extended data points), respectively. Landfillings deriving from different number of times processed materials are identified in a very similar way as was done for the recovery model above. The total amount of landfilling in any year \( j \), \( TL(j) \) can be represented by:

\[
TL(j) = L_L(j) + L_Lx(j) + \sum_{np=0}^{NP} T_L(np,j)
\]

where

\[
T_L(np,j) = \sum_{i=1}^{L_N_j} L(np,j,i) + \sum_{m=1}^{L_N_x_j-1} L_x(np,j,m)
\]

where \( LN_j = N_j \ (j \geq 3) \) and \( LN_x_j = N_x_j - 1 \ (j \geq 2) \)

4. Results

The summary of Fig. 3 is presented in Fig. 4 using Eq. (6) which gives the total amount of material present in the system in any calculation year. The individual component of Eq. (6) is also plotted in Fig. 4. Based on the available virgin plastic import data prior to 1995, the model allows us to predict future recovery and recycling scenarios. Although Fig. 4 only shows the results until 1999, the model can be used to predict scenarios beyond this period. The amount of materials in terms of their ‘number of times processed’ can also be plotted (details in Haque [3]). Similar results (as shown in Fig. 4 for Bangladesh) can also be obtained for India by introducing a few extra modelling parameters such as national production and export of plastic pellets and imports of plastic wastes, along with 30 and 45% recovery rates for 1st and 2nd year, respectively, and 25% for landfilling and other disposal options.

5. Quality factors and legislative measures

Haque [3] observed that a substantial degradation in both the mechanical and rheological properties takes place with successive processing of the HDPE general scraps collected from the plastic waste streams of Bangladesh and India. In particular, drastic falls in both their tensile strength and impact resistance performance occurred around the 5th or 6th times of processing. The results have also shown a decrease in the impact resistance performance and a slight change in the rheological properties with increasing ‘number of successive processing’ (NSP) of the virgin material. In general, the higher the NSP, the lower the quality. Therefore, if new legislative measures come into practice at some point in the near future which will eliminate recycling of the materials already processed more than six times (such a legislative limit for number of successive processing can be denoted as: \( LgNSP > 6 \)), as a consequence of quality deterioration, what would be the consequences for the plastics recycling scenarios of Bangladesh? What would be the changes in the amount of materials recovered and landfilled? The model presented in this work considers this factor which allows generation of future recovery and landfilling scenarios based on hypothetical environmental
legislative limits for plastic recycling. Table 1 presents the summary of the recovery and landfilling scenario with different values of LgNSP. It is clear from Table 1 that there must be a compromise between the quality of the recycled product and the amount landfilled before the value of LgNSP is decided by the government.

6. Conclusions

In this work, a simple model is developed to capture the complex plastic recycling and landfilling scenarios in Bangladesh and to represent the system in a more meaningful way. The model is based on the assumption of a linear virgin plastic import pattern. The recovery
and landfilling (i.e. 2% in the first year and 3% in the second year) strategies based on the field survey contribute the main parameters of the model. If these strategies change at any time in the future, the model parameters can easily be updated. The scenarios presented in this work did not account for the presence of any recyclable or landfilled material before 1990 as there were no official import data available for the virgin plastics. Although the results are presented at ‘1 year intervals (calculation year)’, the model is capable of predicting recovery and landfilling scenarios over much shorter or longer time intervals. Some results with longer time intervals and with different recovery and landfilling strategies are presented in Haque [3] to show the sensitivity of the model parameters on the scenario. An environmental legislative factor has been taken into account as a model parameter, which provides guidelines for an efficient waste management. Finally, the expertise gathered from the mathematical modelling has potential applications and uses in processes where the aspect of exponential expansion and repeated occurrence of the same events/phenomena are involved (e.g. demographic, chemical and bio-chemical processes).

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