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Optimization of an Industrial Recycling Line: The Effect of Processing Parameters on Mechanical Properties of Recycled Polyethylene (PE) Blends

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Abstract: This study concerns the optimization of an industrial recycling line; in other terms, this paper aims to find the optimal processing parameters that allow for a decrease in the loss of stress crack resistance (SCR) using a notched crack ligament stress (NCLS) test and an increase in the gain of the elongation at break, flexural modulus, and Izod impact strength of a polyethylene (PE) blend before and after recycling. The recycling line is composed mainly of a mono- and twin-screw extruder and a filtration system. Hence, the research question is as follows: How can we optimize the recycling process, without compromising the mechanical properties of recycled polyethylene (PE) blends? To answer the research question, Taguchi's design of experiment and grey relational analysis (GRA) for multiobjective optimization was applied. Experiments were performed according to L_{16} standard orthogonal array based on five process parameters: mono-screw design, screw speed of the mono- and twin-screw extruder, melt pump pressure, and filter mesh size. Based on grey relational analysis (GRA), the optimal setting of process parameters was identified, and a barrier screw and a higher screw speed for both extruders were allowed to have optimal mechanical properties. Furthermore, the analysis of variance (ANOVA) indicated that the mono-screw design and screw speed of the mono- and twin-screw extruder significantly impact the mechanical properties of recycled polyethylene (PE) blends.

Keywords: mechanical recycling; polyethylene (PE); stress crack resistance (SCR); grey relational analysis (GRA); analysis of variance (ANOVA)

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1. Introduction

The growth of populations and incomes have increased global plastics production; it has doubled, reaching 460 million tons (Mt) in 2019 [1]. This rapid growth is due to the good properties and low cost of plastic. Thanks to its versatility, this material is used in several fields such as packaging, textile, transport, and construction [2]. Global annual plastic waste increased by more than double between 2000 and 2019. Most of the plastic waste comes from applications with lifespans of less than five years: packaging (40%), consumer products (12%), and textiles (11%) [1]. Indeed, only 9% of plastic waste was recycled, while 19% was incinerated and almost 50% was landfilled. The remaining 22% was burned or leaked in the environment [1]. The proliferation of plastics negatively impacts the environment because of the emission of greenhouse gas emissions, since the production of virgin plastics requires the transformation of petroleum into monomers, which is an energy-intensive mechanism. This process generated more than 400 million tons (Mt) of greenhouse gas emissions in 2012 [3]. Protecting the environment involves reducing plastic footprints and enhancing recycling. Basically, recycling techniques can be classified in three categories: physical recycling (primary and secondary recycling), chemical recycling, and energy recovery (incineration) [4–6]. Physical recycling, also called mechanical recycling, is the most used technique, consisting of several operations (collecting, separating, washing, drying, and extrusion) that aim to obtain a recycled polymer with higher mechanical properties [7].

Mixing polymers during extrusion is one of the most important factors that influences recycled blend properties [8,9]. Some qualitative visualization techniques had demonstrated that the mixing quality of polymer is affected by the design of the mixing element. The capability to create a high shear rate was an essential property that enhanced mixing. It was found that the best emplacement of the mixing element is just after the melting zone. Moreover, screw speed was also an important factor that influenced mixing quality, and among all the mixing elements tested, the pineapple screw offered the best mechanism for polymer mixing [8]. The recycling line under study is equipped with a mono- and twin-screw extruder and a filtration system. Each piece of equipment has several parameters. To optimize the process's parameter, a design of experiment was completed based on Taguchi coupled with grey relational analysis (GRA).

The Taguchi method helps to design and analyze experiments [10]. It has proved its efficiency to significantly reduce the number of trials without compromising the quality of products. However, this method has been developed to optimize a few performance characteristics. Studying multiple performance characteristics requires using the Taguchi method combined with other methods [11]. Some researchers have highlighted Taguchi's quality loss function to determine optimum conditions during the parameter design stage for optimizing multiple quality characteristics in manufacturing processes [12,13]. The fuzzy logic Taguchi method was used by several researchers to optimize processes with multiple performance characteristics [14,15]. Some researchers used the Taguchi coupled with grey relational analysis (GRA) to optimize process parameters; Huang and Lin applied the grey relational analysis for the optimization of machining parameters of wire EDM [16]. Fung and al. studied the grey relational analysis to obtain the optimal parameters of the injection molding process for mechanical properties of yield stress and elongation in polycarbonate/acrylonitrile–butadiene–styrene (PC/ABS) composites [17]. C. L. Lin used the Taguchi method and grey relational analysis to optimize turning operations with multiple performance characteristics [18].

As mentioned before, this paper focuses on the optimization of the industrial recycling line composed of several pieces of equipment such as extruders and filtration systems. This industrial line is dedicated to recycling polyethylene (PE) blends, which will be used to produce corrugated pipes. The main objective of this study is to investigate the effect of process parameter (RPM, filter mesh size, melt pump pressure, and mixing element) on the mechanical properties of (PE) a polyethylene (PE) blend, such as elongation at break, flexural modulus, Izod, and stress crack resistance (SCR).

2. Materials and Methods

2.1. Recycling Line and Materials

The recycling line consists of several components, which can be divided into two sections: the first (single-screw extruder + filtration system) for decontamination, and the second (twin-screw extruder) for homogenization (Figure 1).

Figure 1. Recycling line components.

The reference blend tested was composed of recycled high molecular weight polyethylene (rHMW) and recycled high-density polyethylene (rHDPE) (Table 1).

Table 1. Blend's composition.

Composition	Rate (%)
rHMW	62.5
rHDPE	37.5

Two screw designs were tested in the mono-screw extruder: a barrier screw and a screw equipped with Maddock and pineapple mixer (Figure 2).

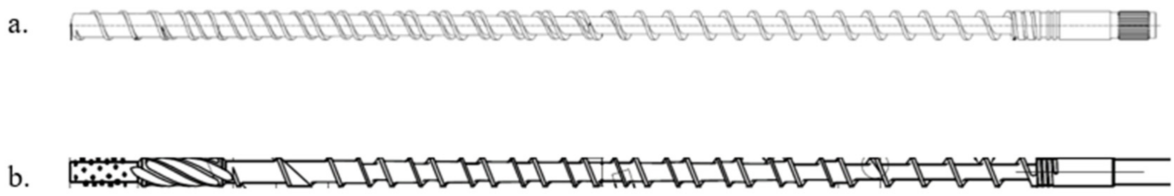


Figure 2. (**a**) Barrier screw (**b**) Screw with Maddock and pineapple.

The temperatures of the mono- and twin-screw extruder were chosen depending on the polymer blend composition (Tables 2 and 3).

Table 2. Mono-screw extruder temperatures.

T (°C)	220	240	235
Zone	1	2–4	5–7

Table 3. Twin-screw extruders temperatures.

T (°C)	200	210	215	225	235	220
Zone	1	2	3	4	5–7	7–12

2.2. Experimental Methodologies

2.2.1. Tensile Test

Tensile tests were performed in accordance with ASTM D638-14, on five dog-bone-shaped specimens (specimen type IV) cut from a 3.2 mm thick molded plate (Figure 3). Tensile tests were carried out on a lab integration machine with a crosshead speed of 50 mm/min at room temperature 23 °C. Elongation at break was determined from stress–strain curves [19].

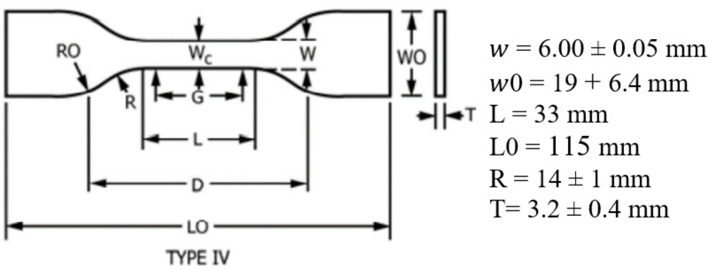


Figure 3. Dimensions of tensile test's specimen [19].

2.2.2. Bending Test

Bending tests were performed in three-point bending mode with a crosshead speed of 10 mm/min according to ASTM D790 on five test rectangular specimens (Figure 4) [20]. The flexural modulus was determined from stress–strain curves.

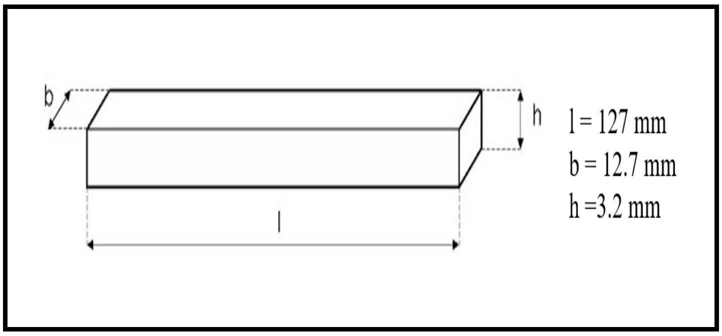
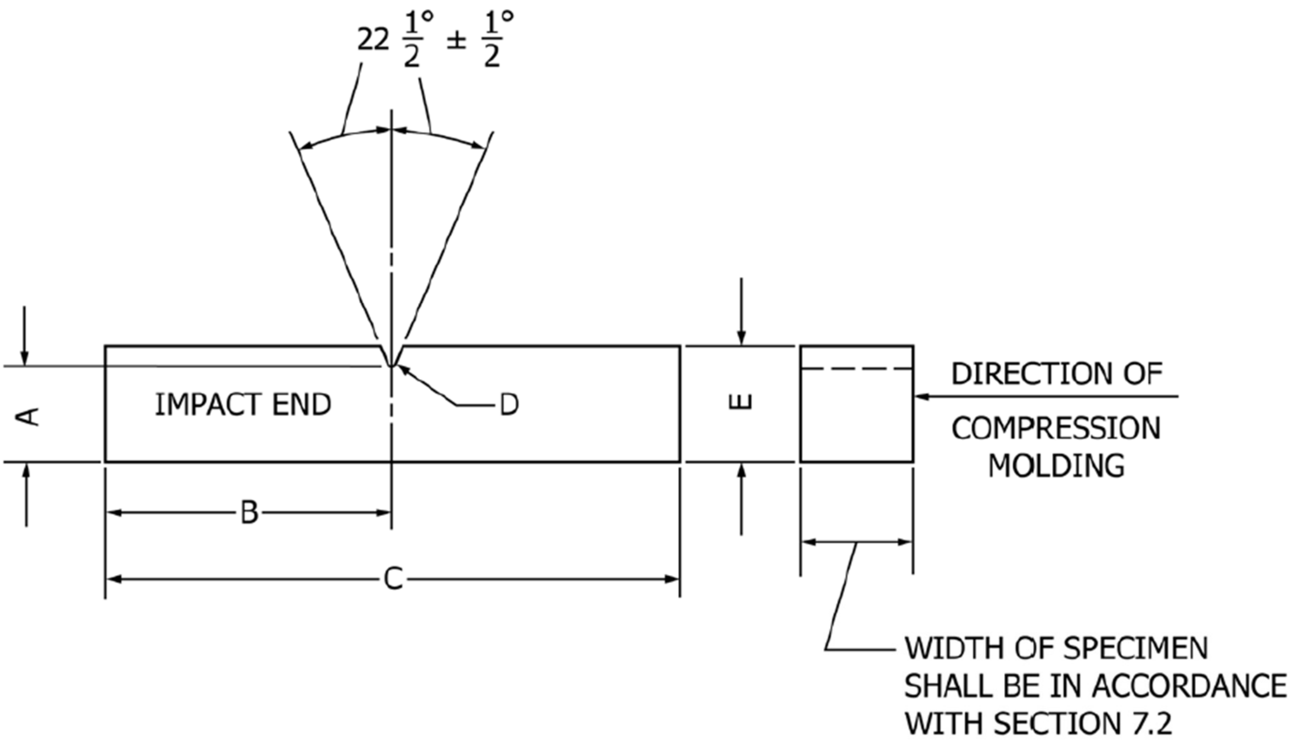


Figure 4. Dimensions of bending test's specimen [20].

2.2.3. Impact Test Izod

An Izod test is a standardized impact test used to measure the energy absorbed by a material when a notched specimen is subjected to a sudden impact load. This test was performed on an Izod impact tester according to the ASTM D256-10 [21].

The 8 notched specimens with a V-shape notch, with dimensions that are illustrated in Figure 5, were tested using a pendulum. The energy absorbed by the specimen during the test indicates the material's toughness and its impact resistance.



	mm	in.
A	10.16 ± 0.05	0.400 ± 0.002
B	31.8 ± 1.0	1.25 ± 0.04
C	63.5 ± 2.0	2.50 ± 0.08
D	0.25R ± 0.05	0.010R ± 0.002
E	12.70 ± 0.20	0.500 ± 0.008

Figure 5. Dimensions of Izod type test specimen [21].

2.2.4. Notched Crack Ligament Stress (NCLS)

Based on ASTM F2136, this test method is intended to assess slow crack growth (SCG) for polyethylene (PE) resin. In other terms, this test is used to control the tenacity of materials. The test specimen (Figure 6), which is obtained from compression-molded plaques, is notched and immersed in a solution composed of distilled water and 10% Igepal, at a temperature of 50 °C. Five specimens were placed at a single ligament stress level in a bath maintained at 50 °C, the weight tube was attached to the lever arm of each specimen, and the time to failure of all specimens was recorded [22].

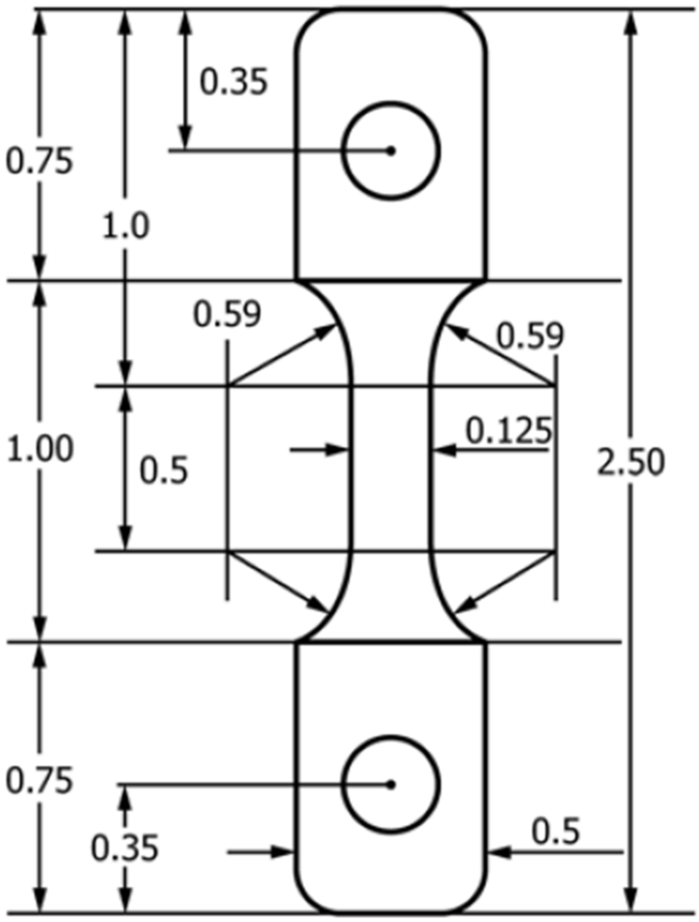


Figure 6. NCLS's specimen geometry [22].

2.3. Design of Experiments

2.3.1. Line's Parameters

The design of experiments (DOE) approach based on the Taguchi method has been applied in several studies related to composite and polymer processes [23–25].

By using strategically this method, it is possible to study the effect of several variables at one time, and to study inter-relationships and interactions [26–28].

The objective of this paper is to study the effect of recycling line parameter on the mechanical properties of recycled polyethylene (PE) blends and to determine the optimal parameters configuration of the line.

The parameters considered were as follows: the screw design of the mono-screw extruder, the screw speed of the mono- and twin-screw extruder, the mesh size of the filter, and the pressure of the melt pump. Taguchi orthogonal arrays (OA) were used to build the experimental matrix. Table 4 shows the parameters and their levels in the experiments.

Table 4. Experimental parameters and their levels.

Factors	Parameters	Levels	
A	Mono-screw design	Maddock + Pineapple	Barrier screw
B	Screw speed 1 (mono-screw extruder)	80	90
C	Pressure melt pump (bar)	35	40
D	Filter mesh size (μm)	200	300
E	Screw speed 2 (mono-screw extruder)	210	225

2.3.2. Taguchi Orthogonal Arrays (OA) Design

The Taguchi experimental design, called orthogonal arrays (OAs), consists of a set of fractional factorial designs which ignore interactions and concentrate on main effect estimation. Orthogonal arrays can be viewed as plans of multifactor experiments where the columns correspond to the factors, the entries in the columns correspond to the test levels of the factors, and the rows correspond to the tests (Table 5).

Table 5. Experimental design based on experimental values.

Exp. No.	Mono-Screw Design	Screw Speed (Mono-Screw Extruder)	Melt Pump Pressure	Mesh Size Filter	Screw Speed (Twin-Screw Extruder)
1	Maddock + Pineapple	80	35	200	210
2	Maddock + Pineapple	80	35	300	225
3	Maddock + Pineapple	80	40	200	225
4	Maddock + Pineapple	80	40	300	210
5	Maddock + Pineapple	90	35	200	225
6	Maddock + Pineapple	90	35	300	210
7	Maddock + Pineapple	90	40	200	210
8	Maddock + Pineapple	90	40	300	225
9	Barrier screw	80	35	200	225
10	Barrier screw	80	35	300	210
11	Barrier screw	80	40	200	210
12	Barrier screw	80	40	300	225
13	Barrier screw	90	35	200	210
14	Barrier screw	90	35	300	225
15	Barrier screw	90	40	200	225
16	Barrier screw	90	40	300	210

3. Results and Discussions

3.1. Results of Experiments

After setting the experimental parameters for each experiment, 16 experiments were conducted using Taguchi orthogonal arrays (Table 5). Four characterization tests were carried out on the recycled materials. In other terms, the response features were elongation at break, flexural modulus, Izod impact strength, and stress crack resistance (SCR).

Since the study concerns an industrial line that recycles post-consumer and post-industrial plastics from all sources, the physicochemical properties of its materials change depending on the batch. To overcome this complexity, for each test, three samples were characterized before and after they had been recycled, and the gain of each property was calculated for all the tests (Table 6).

Table 6. Data summary of experiments.

Exp. No.	A	B	C	D	E	Elongation at Break (%)	Stress Crack Resistance (%)	Flexural Modulus (%)	Izod Impact Strength (%)
1	1	1	1	1	1	210	−81.2	19.2	22.3
2	1	1	1	2	2	43	−79.4	30.4	25.7
3	1	1	2	1	2	122	−80.1	2.6	35.2
4	1	1	2	2	1	100	−80.3	33.3	38.4
5	1	2	1	1	2	177	−87.2	19.3	21.1
6	1	2	1	2	1	271	−82.7	28.2	25.8
7	1	2	2	1	1	19	−81.9	8.8	14.3
8	1	2	2	2	2	181	−80.6	33.7	15.2
9	2	1	1	1	2	134	−64.5	12.9	17.9
10	2	1	1	2	1	237	−75.5	13.2	26.3
11	2	1	2	1	1	31	−79.3	8.0	22.4
12	2	1	2	2	2	182	−72.2	4.4	22.8
13	2	2	1	1	1	94	−63.1	11.3	17.5
14	2	2	1	2	2	174	−57.4	7.7	19.5
15	2	2	2	1	2	118	−72.6	14.9	17.5
16	2	2	2	2	1	255	−61.3	20.2	19.5

To investigate which processing parameters significantly affect the mechanical properties of the recycled blends, graphics were drawn using Minitab to shows the effect of each parameter on each recycled blend's property (Figures 7–10).

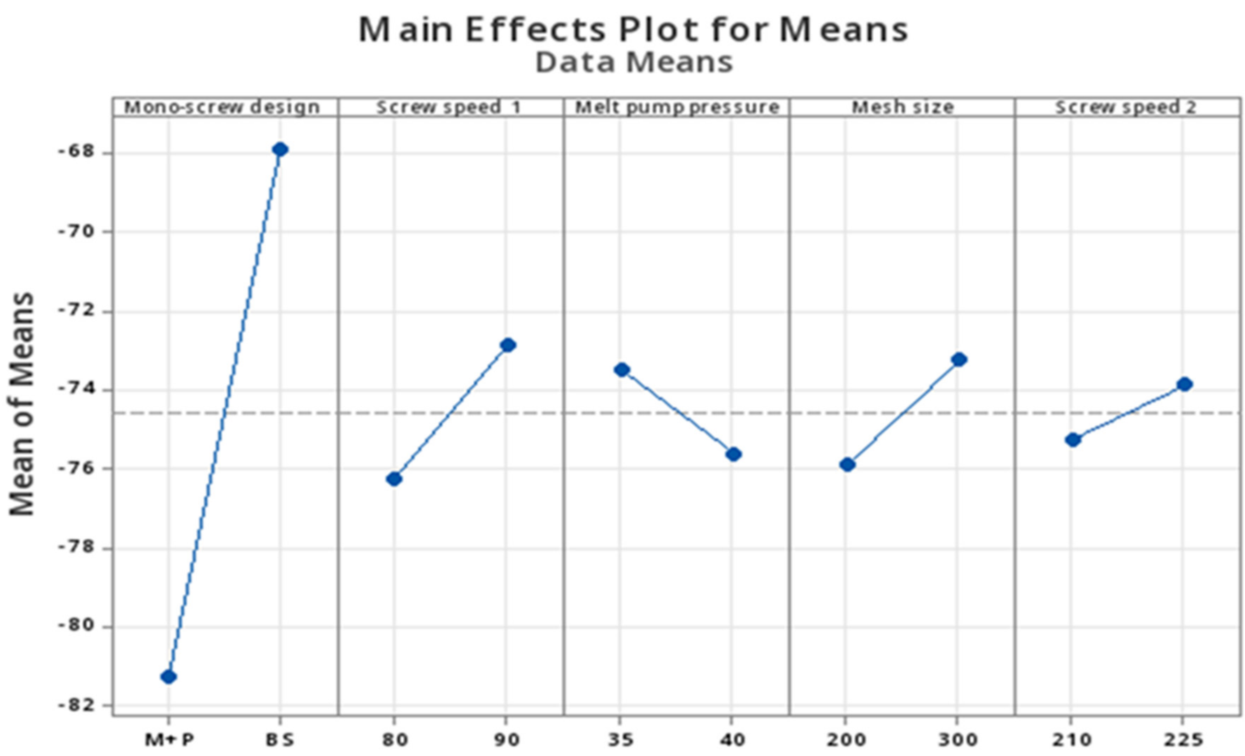


Figure 7. The gain of stress crack resistance (%) vs. line's parameters.

Figure 8. The gain of elongation at break (%) vs. line's parameters.

Figure 9. The gain of flexural modulus (%) vs. line's parameters.

Figure 10. The gain of Izod impact strength (%) vs. line's parameters.

The graphics show that the design of the mono-screw extruder significantly influences the gain of elongation at break and the loss of SCR (stress crack resistance), while the pressure of the melt pump and the screw speed of the twin-screw extruder impact the gain of Izod impact strength and flexural modulus, respectively.

Since the process has 4 response features, and each parameter has a significative impact on only one property, the Taguchi method should be coupled with grey relational analysis (GRA) to figure out the optimal parameters configuration that improve the mechanical properties under study of the recycled blend.

3.2. Grey Relational Analysis

Grey relational analysis (GRA) is a method that combines all the considered performance characteristics into a single value that can be used as the single characteristic in optimization problems. This approach is based on the normalizing of data, and the calculation of grey relational grade (GRG) using grey relational coefficient (GRC) [29].

3.2.1. Normalization of Responses Values

Normalization of response values are completed to transfer the original sequence to a comparable sequence. Numerical results are normalized between 0 and 1. The normalization can be divided to two types depending on the expected nature of the response.

The first normalization is 'the smaller the better' values, where the lowest values of the function are expected. The second one is 'the higher the better', where the highest values of the results are expected.

Since the objective of the study is to find the parameters that allow for the production of a recycled material with optimal properties, accordingly, 'the higher the better' is the normalization criteria that is considered.

The formula for 'the higher the better' normalization criteria considered is as follows:

$$X_i(k) = \frac{Y_i(k) - \min Y_i(k)}{\max Y_i(k) - \min Y_i(k)} \quad (1)$$

where

- $X_i(k)$: value after the grey relational generation.
- $Y_i(k)$: the original data.
- min $Y_i(k)$: smallest value of the response $Y_i(k)$.
- max $Y(k)_i$: largest value of the response $Y_i(k)$.

Hence, the normalized values of the responses are calculated and presented in Table 7.

Table 7. Normalized experimental results.

Exp. No.	Normalization			
	Stress Crack Resistance	Elongation at Break	Flexural Modulus	Izod Impact Strength
1	0.2	0.76	0.56	0.33
2	0.26	0.09	0.91	0.38
3	0.24	0.41	0.06	0.86
4	0.24	0.32	1	0.99
5	0	0.63	0.56	0.28
6	0.17	1	0.84	0.47
7	0.18	0	0	0
8	0.21	0.64	1	0.04
9	0.77	0.46	0.37	0.15
10	0.42	0.87	0.4	0.49
11	0.26	0.05	0.26	0.33
12	0.20	0.65	0.1	0.35
13	0.81	0.3	0.34	0.13
14	1	0.62	0.21	0.21
15	0.49	0.4	0.59	0.57
16	0.89	0.94	0.42	1

3.2.2. Grey Relational Grade

The grey relational grade (GRG) is used to measure the correlation between the measurement spaces factor and the target sequence after a grey relational generation of the discrete sequence. The GRG depends on grey relation coefficient $\gamma_i(k)$, which can be calculated using the following equation:

$$\gamma_i(k) = \frac{\Delta_{\min+}\xi\Delta_{\max}}{\Delta_{0i}(k) + \xi\Delta_{\max}} \tag{2}$$

where

- $\Delta_{0i} = ||X_0(k) - X_i(k)||$: which is the difference of the absolute value between the target sequence $X_0(k)$ and the comparison sequence $X_i(k)$.
- ξ: distinguishing coefficient: 0.5.
- $X_0(k)$: the target sequence.
- $X_i(k)$: the calculated sequence.
- $\Delta_{\max}$ = max $\Delta_{0i}(k)$
- $\Delta_{\min}$ = min $\Delta_{0i}(k)$

After the calculation of the GRA coefficient, the grey relational grade can be calculated by the following equation:

$$\gamma = \frac{1}{n}\sum_{i=1}^{n}\gamma_i(k) \tag{3}$$

Table 8 shows the grey relational coefficients and grades for each experiment.

Table 8. Grey relational coefficients and grey relational grades.

Exp. No.	Grey Relational Coefficient				Grey Relational Grade	Ranking
	Stress Crack Resistance	Elongation at Break	Flexural Modulus	Izod Impact Strength		
1	0.38	0.75	0.53	0.46	0.53	7
2	0.4	0.33	0.4	0.45	0.395	15
3	0.4	0.4	0.41	0.82	0.507	8
4	0.4	0.42	0.86	0.69	0.592	3
5	0.32	0.47	0.46	0.4	0.412	14
6	0.38	0.59	0.44	0.43	0.46	12
7	0.38	0.35	0.33	0.33	0.347	16
8	0.39	0.53	0.56	0.33	0.452	13
9	0.68	0.49	0.38	0.36	0.477	10
10	0.46	0.93	0.47	0.48	0.585	4
11	0.4	0.42	0.64	0.42	0.470	11
12	0.5	0.63	0.38	0.43	0.485	9
13	0.73	0.49	0.71	0.36	0.572	5
14	1	0.49	0.4	0.38	0.567	6
15	0.5	0.56	1	0.54	0.65	2
16	0.82	1	0.53	1	0.837	1

The higher grey relational grade (GRG) corresponds to the optimal parameter combination. Experiment 16 has the highest value of grey relational grade, and the factors set up for this experiment are listed in Table 9.

Table 9. Parameter's optimal values.

Parameters	Optimal Values
Mono-Screw design	Barrier screw
Screw speed (mono-screw extruder)	90
Pressure melt pump	40
Filter mesh size	300
Screw speed (twin-screw extruder)	210

The means of the grey relational grade for each level of the five parameters are calculated in Table 8 and summarized in Table 10. Figure 11 shows the process parameter in relation with the grey relational grade.

Table 10. Mean value of the grey relational grade.

Factors	Level 1	Level 2	Max-Min	Rank
Mono-screw design	0.453	0.608	0.155	1
Screw speed (mono-screw extruder)	0.503	0.558	0.055	3
Pressure melt pump	0.526	0.529	0.003	5
Filter mesh size	0.506	0.554	0.048	4
Screw speed (twin-screw extruder)	0.558	0.502	0.056	2

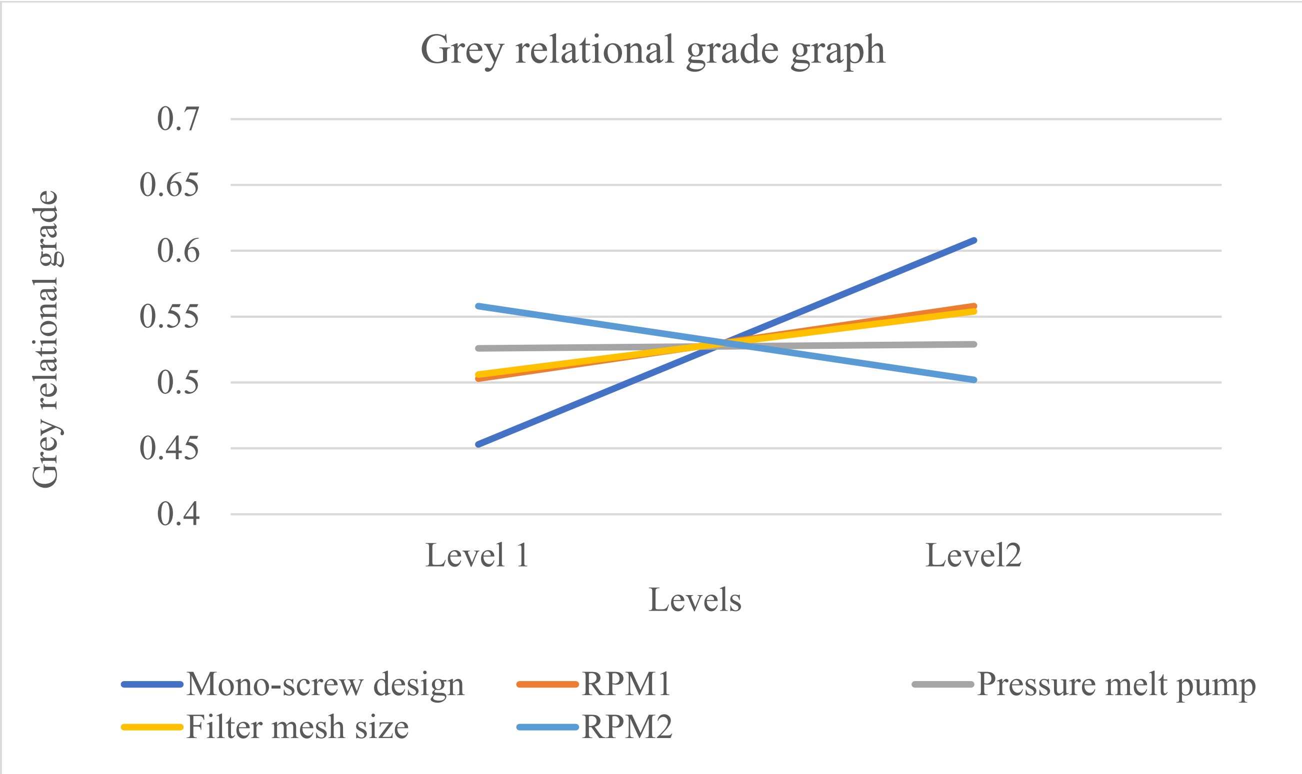


Figure 11. Grey relational grade graph.

Based on Figure 11 and Table 10, the mono-screw design and the RPM of the two extruders significantly influence the grey relational grade and, consequently, impact the mechanical properties of the recycled blends.

3.3. ANOVA Analysis

The analysis of variance (ANOVA) is a method used in this study to find which controllable parameter significantly affects the feature responses of this process. The main objective of ANOVA is to extract from the results how much variation each factor causes to the total variation observed in the results [30]. The ANOVA indicates the percentage and the degree of influence of each factor on the results obtained (Table 11).

The results of the ANOVA indicate that the percentage of contribution of the mono-screw design, screw speed of the mono- and twin-screw extruder, and mesh size of the filter are 45.47%, 5.7%, 5.86%, and 4.3%, respectively (Table 11).

Figure 12 shows the contribution of the five parameters on the mechanical properties of recycled blends. The mono-screw design is the most significant parameter for multiple performance characteristics, while the melt pump pressure does not have a significant impact on the process's response.

Table 11. ANOVA for multiple performance characteristics.

Factors	Degrees of Freedom	Sum of Squares (SS)	Mean Squares Variance (MS)	F Value	Contribution (%)
A	1	0.09641	0.09641	11.78	45.47
B	1	0.0121	0.0121	1.48	5.7
C	1	0.0001	0.0001	0.01	0.04
D	1	0.00912	0.00912	1.11	4.3
E	1	0.012432	0.012432	1.52	5.86
Error	10	0.081855	0.008186		
Total	15	0.212018			

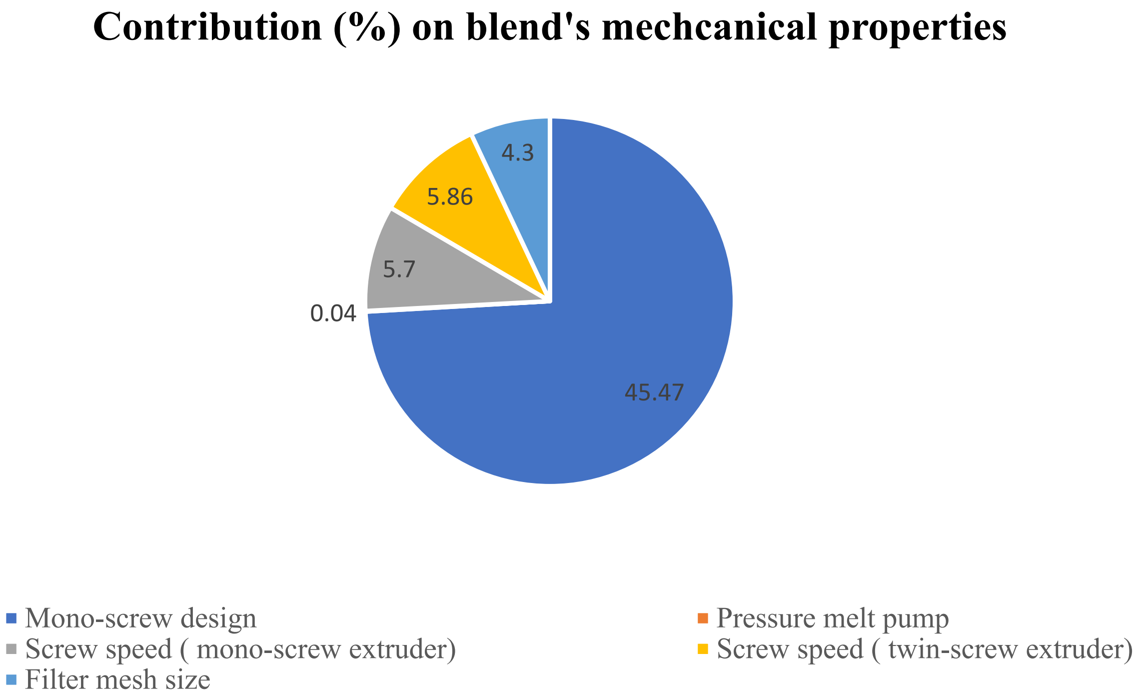


Figure 12. Contribution (%) on blend's mechanical properties.

4. Conclusions

In this paper, the controllable parameters influencing the multiple performance characteristics of recycled polyethylene (PE) blend were studied based on Taguchi's experimental design method. The optimal configuration of the recycling line was determined for the improvement in the following mechanical properties: elongation at break, flexural modulus, Izod impact strength, and stress crack resistance (SCR).

This research proposed the orthogonal array combined with the grey relational analysis (GRA) to optimize multiple performances of recycling of PE blends when 5 parameters where modified: mono-screw design, speed screw of the mono- and twin-screw extruder, the pressure of the melt pump, and the mesh size of the filter.

The conclusions were summarized as follows:

1. It can be concluded from the grey relational grade and the response table for the grey relational grade that the optimal levels of recycling process parameters for the desired mechanical properties is the combination labelled as A2B2C2D2E1. In other terms, the optimal parameter settings are as follows:

- Mono-screw design: Barrier screw
- Screw speed (mono-screw extruder): 90 RPM
- Pressure of the melt pump: 40 bar
- Mesh size of the filter: 300 µm

- Screw speed (twin-screw extruder): 210 RPM

With this combination, it is possible to have a lower decrease in stress crack resistance (SCR) and higher elongation at break, Izod impact strength, and flexural modulus.

2. Based on the ANOVA of the GRG results, it is observed that mono-screw design, screw speed of the mono- and twin-screw extruder has a significant influence on the recycled blend properties.

However, since the study concerned an industrial recycling line developed for recycled polyethylene (PE) blends, these findings could not be generalized to other types of recycled polymers. For perspective, a second part of this study is under preparation to analyze the effects of process parameters on contaminants presents in polyethylene (PE) blends before and after recycling.

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