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Optimisation of Injection Moulding Process Parameters

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ABSTRACT

It is crucial to develop new techniques for recycling or reusing plastic components given their widespread manufacture and the fact that natural processes cannot break them down. Injection moulding, among the most common plastic processing processes, allows recycled materials to be swapped for virgin material during the manufacturing process of plastic objects. Furthermore, the primary challenge that significantly limits the application of recycled plastic is the loss of the mechanical qualities of recycled plastic components. The presence of variability in the processing parameters is one of the most important contributing elements. During the production process, it is of the utmost importance to successfully regulate all influencing processing parameters by utilizing an appropriate optimisation strategy. Considering this, the primary purpose of this research is to study the effect that the best parameters used for injection moulding have on the mechanical qualities of recycled plastic components.

1. Introduction

In recent years, there has been a great deal of debate and research on plastics and the processes used to make them [1]. Due to their many advantages over other materials and ease of moulding, plastics are widely used in today's world for a variety of purposes. They also have low heat and electricity conductivity, are lightweight, very affordable, and resistant to bacteria, chemicals, and sunlight. As a result, plastics have developed into a versatile material that can take the place of conventional materials like metal and wood [2].

Plastic materials can be produced using a variety of processing techniques [3]. Most manufacturing companies use injection moulding as a crucial technique when producing plastic

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goods [2,3]. Gas-assisted injection moulding, compression resin transfer moulding, thermoforming and vacuum forming, rotational transfer moulding, and plastic extrusion are additional techniques for processing plastic [4–6]. Plastics' adaptability for particular applications and versatility have been the main forces behind their steady growth, which is anticipated to continue as a result of new processing methods.

The consumption of plastic has rapidly increased over the past few decades, with nearly 350 million tons produced annually, according to research by Heidbreder, Bablok, Drews, and Menzel [9]. This increase in production could result in serious global environmental pollution [10]. Additionally, a significant amount of fossil fuels is needed to produce plastic in factories around the world, both as a source of energy and raw materials. According to estimates, 4% of the world's annual oil production is used as a feedstock for making plastics, and an additional 3–4% is used up during production. Recycling plastics is one possible way to address this problem and lessen environmental pollution [11]. Plastics can be gathered and recycled to make new functional components. Recycling preserves and reuses the oil used in the production of plastic for a longer time, which is good for the environment.

One technique for making plastics that uses recycled plastic in place of raw material is injection moulding [12]. This lowers the demand for raw plastic materials and helps preserve the environment. Unfortunately, because recycled plastic's mechanical properties are inferior to those of raw materials, manufacturers frequently choose raw materials over recycled ones. In the manufacturing sector, management frequently puts profits and consumer satisfaction ahead of environmental considerations. In terms of mechanical properties, recycled materials have not proven to be reliable sources. Takatori's research from 2015 [13] indicates that the main causes of changes in the mechanical properties of recycled plastics are impurities added during the crushing and reheating processes. Although it is difficult to create recycled plastic parts with virgin plastic's mechanical properties, it is possible to maximize the mechanical properties of these recycled materials by meticulously controlling key manufacturing processing variables [14-16].

The goal of this study is to look into and pinpoint the crucial injection moulding process variables that affect mechanical properties like tensile strength and flexural modulus [11–13]. By fine-tuning particular injection moulding process variables, it also aims to maximize the mechanical characteristics of recycled polypropylene, such as tensile strength and flexural modulus [17-19]. The ultimate objective is to establish a quantitative relationship between mechanical characteristics and process variables in order to investigate whether recycled plastic can replace virgin plastic in certain applications based on mechanical properties.

2. Methodology

This study is divided into three primary phases: selecting process parameters and characteristics, optimising process parameters, and establishing quantitative relationships. The steps for each phase are shown in Figure 1. During the first phase, an explanation of selecting the appropriate process parameters and quality characteristics will be provided. To optimise the process, it will be divided into two parts. The Taguchi experiment and the mechanical testing that will be done will be the primary topics of discussion during the explanation of the first phase of optimisation. When it comes to the second stage of the optimisation process, the focus will be placed on the desirability function as well as verification studies. In conclusion, the method that will be discussed will be one that can establish a quantitative relationship between the process parameter and the quality characteristic.

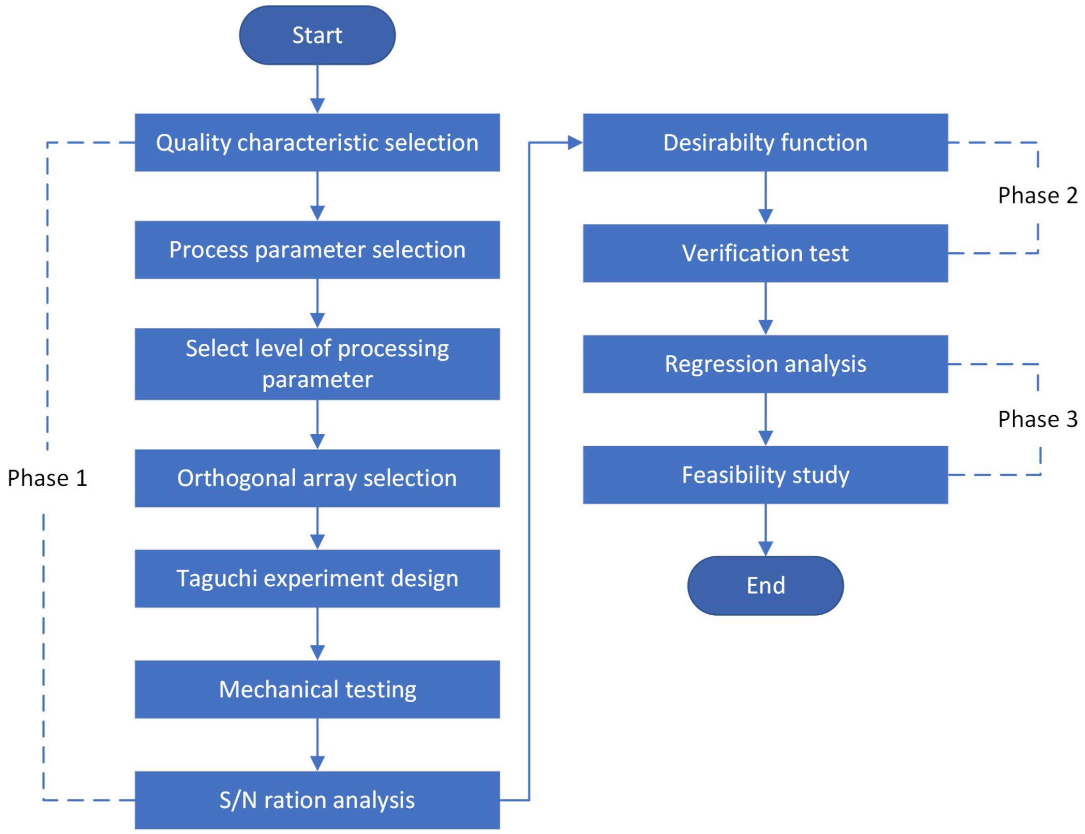

Fig. 1. Flow chart of methodology

2.1 Phase 1: Process Parameter and Characteristic Selection
2.1.1 Characteristic selection

To begin research, select the desired product quality and optimise its performance. Product quality can be divided into dimensional, surface, and mechanical properties. This investigation focuses on the impact of processing parameters on recycled polypropylene's mechanical properties by measuring tensile strength and flexural modulus in injection-moulded specimens [20-24].

2.1.2 Process parameter selection

Plastic injection moulding quality is influenced by various factors, including raw material, machine, and mould design. Controlling injection moulding process conditions is crucial for smooth moulding and part quality. Temperature, pressure, time, and distance are the four fundamental parameters. Eight process factors significantly impact mechanical properties: holding pressure, holding time, injection pressure, speed, duration, melt temperature, cooling time, and mould temperature. The temperature of the mould was not chosen as a processing parameter due to the lack of equipment for mould temperature evaluation in injection moulding machines [16-17].

2.1.3 Level selection

The number of levels for each independent variable depends on the performance parameter's relationship with the dependent variable. Levels 3, 4, or higher are chosen based on the relationship between the variables. This research used a three-level approach for parameter analysis and optimisation. Key process elements were carefully selected to affect performance characteristics and

Tests were conducted using the Taguchi orthogonal array. Process parameters such as holding pressure, holding time, cooling time, melting temperature, injection pressure, speed, and injection time were selected to control the plastic product's quality and output [20, 25]. Tab. 1 describes the parameters at each level of the selected process.

Table 1
Selected process parameters

Process Parameter	Level 1	Level 2	Level 3
Melt temperature	180	220	260
Injection pressure	45	50	55
Injection speed	20	25	30
Injection time	6	7	8
Holding pressure	20	35	50
Holding time	1	2	3
Cooling time	15	20	25

2.1.4 Orthogonal array selection

Orthogonal arrays are a conventional experimental design that requires a minimum of 15 trials to evaluate key components' effects on output. Standard orthogonal arrays are commonly used to design experiments: L4, L8, L12, L16, and L32 as 2-level arrays; L9, L18, and L27 as 3-level arrays; and L16 and L32 as 4-level arrays. To optimise parameters, 27 experiments are required, with L27 chosen for precise data sampling. Level combinations are used to select experiments, and each experiment's performance parameter is recorded for analysis.

2.1.5 Experimental design

The Taguchi experimental design is developed when the orthogonal array has been selected as the layout for the data. The quantity of parameters and values is used to determine which orthogonal array to use, and that array is L27. It is made up of seven different components, each of which has three different levels. The selected process parameters and their preliminary parameter values are tabulated as follows in Table 2 below, using the L27 orthogonal array system design as the basis for the tabulation. To carry out the experiment, you will need 27 different parameter configurations. To ensure quality control, three samples have been selected. In order to offer precise quality findings for each set of parameters, a total of 81 separate tests were carried out.

Table 2
L27 orthogonal array

No	Melting temperature	Injection pressure	Injection speed	Injection time	Holding pressure	Holding time	Cooling time
1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2
3	1	1	1	1	3	3	3
4	1	2	2	2	1	1	1
5	1	2	2	2	2	2	2
6	1	2	2	2	3	3	3
7	1	3	3	3	1	1	1
8	1	3	3	3	2	2	2
9	1	3	3	3	3	3	3
10	2	1	2	3	1	2	3
11	2	1	2	3	2	3	1
12	2	1	2	3	3	1	2
13	2	2	3	1	1	2	3
14	2	2	3	1	2	3	1
15	2	2	3	1	3	1	2
16	2	3	1	2	1	2	3
17	2	3	1	2	2	3	1
18	2	3	1	2	3	1	2
19	3	1	3	2	1	3	2
20	3	1	3	2	2	1	3
21	3	1	3	2	3	2	1
22	3	2	1	3	1	3	2
23	3	2	1	3	2	1	3
24	3	2	1	3	3	2	1
25	3	3	2	1	1	3	2
26	3	3	2	1	2	1	3
27	3	3	2	1	3	2	1

2.1.6 Mechanical testing

Tensile tests will be conducted to determine material tensile stress, strain, and Young's modulus. The procedure will use a Type 1 tensile bar and a 5 kN load cell, with the crosshead pushed at a consistent pace until the specimen breaks. Flexural properties will be assessed according to ASTM D790, with flexural modulus and modulus measured. The results will be averaged to arrive at a conclusion.

2.1.7 S/N Analysis

The Taguchi method uses mean-squared deviation (MSD) formulas to combine data from multiple trials, calculate variation based on product attributes, and use equations for different quality criteria.

$$Smaller : MSD = \frac{1}{n}\sum_{i=1}^{n} {Y_i}^2 \quad (1)$$

$$Nominal : MSD = \frac{1}{n}\sum_{i=1}^{n} (Y_i - \bar{Y})^2 \quad (2)$$

$$\text{Bigger} : MSD = \frac{1}{n}\sum_{i=1}^{n} \frac{1}{{Y_i}^2} \quad (3)$$

where n represents the number of trials, y represents the value acquired in each trial, and y represents the mean value. The MSD values are then used to calculate a signal-to-noise (S/N) ratio. Formula to calculate the S/N ratio:

$$Smaller : \frac{S}{N} = -10\ log10(MSD) \tag{4}$$

$$Nominal : \frac{S}{N} = -10\ log10\left[\frac{Y^{-2}}{\sigma 2}\right] \tag{5}$$

$$\text{Bigger} : \frac{S}{N} = -10\ log10(MSD) \tag{6}$$

2.2 Phase 2: Optimising Process Parameters
2.2.1 Composite desirability

The desirability function, "D," integrates multiple responses into a dimensionless function for optimising multiple responses simultaneously. The procedure involves converting each response (Yi) into a dimensionless function called the individual desirability function (Di), which ranges from zero to one. If Yi is at its goal, Di = 1; otherwise, Di = 0. (Worst-case scenario.) The desire function assumes that the weight component, w, is a positive integer. The weights for the response variables have been set to one for faster completion of the investigation. In this investigation, we derived individual desirability functions using equations 1–2 based on the type of optimisation function, either maximisation or minimization. If the target value for variable yi is a maximum, the desirability will be determined by the equation below. To reduce costs, an equation will determine what is desirable. The attractiveness can be computed with an equation within the bounds of Ozcelik and Sonat [22].

$$D_i = \begin{Bmatrix} 0 & Y_i < L_i \\ \frac{Y_i - L_i}{T_i - L_i} & L_i \le Y_i \le T_i \\ 1 & Y_i > T_i \end{Bmatrix} \tag{7}$$

$$D_i = \begin{Bmatrix} 1 & Y_i < L_i \\ \frac{T_i - Y_i}{T_i - L_i} & L_i \le Y_i \le T_i \\ 1 & Y_i > T_i \end{Bmatrix} \tag{8}$$

$$D_i = \begin{Bmatrix} 1 & Y_i < L_i \\ \frac{T_i - Y_i}{T_i - L_i} & L_i \le Y_i \le T_i \\ \frac{U_i - Y_i}{U_i - L_i} & Y_i > T_i \\ 0 & \end{Bmatrix} \tag{9}$$

The desirability functions are combined into a single function called overall desirability (D), which ranges from 0 to 1. The equation uses wi to weigh each di assigned to the ith response, and n is the number of responses received. It is the weighted geometric mean of the desirability functions mentioned earlier. We can determine parameter values using a reduced gradient method with multiple starting points. This maximises human desirability (D).

$$D = ({D_1}^{W_1} \times {D_2}^{W_2} \times {D_3}^{W_3} \times \cdots \times {D_n}^{W_n})^{\overline{\frac{1}{(w_1 + w_2 + w_3 + \cdots + w_n)}}} \tag{10}$$

$$D = \prod_{i=1}^{n} D_1^{W_1^{\frac{1}{\sum_{i=1}^{n} w^1}}} \quad (11)$$

2.3 Phase 3: Establishing Quantitative Relationships

Regression analysis is a method used to determine the relationship between process parameters and quality parameters. It generates a mathematical description of the relationship between independent factors and a dependent variable. Different regression models exist, with linear regression being the most common and easiest to understand. It helps understand how the dependent variable changes on average when each independent variable shifts by one unit. Line plots, stepwise regression, and best subset regression are additional options for linear regression.

3. Results
3.1 The Taguchi Experiment
3.1.1 Experimental design

The mechanical properties of the recycled polypropylene are affected by important processing parameters, which are identified and chosen in this work through an experiment. A Taguchi experimental table is created to accomplish the goal. The L27 Taguchi orthogonal array (OA), which was utilised to design out the entire experiment, is displayed in the Table 3 below.

Table 3
Taguchi experimental design

Experiment	Melting temperature	Injection pressure	Injection speed	Injection time	Holding pressure	Holding time	Cooling time
1	180	45	20	6	20	1	15
2	180	45	20	6	35	2	20
3	180	45	20	6	50	3	25
4	180	50	25	7	20	1	15
5	180	50	25	7	35	2	20
6	180	50	25	7	50	3	25
7	180	55	30	8	20	1	15
8	180	55	30	8	35	2	20
9	180	55	30	8	50	3	25
10	220	45	25	8	20	2	25
11	220	45	25	8	35	3	15
12	220	45	25	8	50	1	20
13	220	50	30	6	20	2	25
14	220	50	30	6	35	3	15
15	220	50	30	6	50	1	20
16	220	55	20	7	20	2	25
17	220	55	20	7	35	3	15
18	220	55	20	7	50	1	20
19	260	45	30	7	20	3	20
20	260	45	30	7	35	1	25
21	260	45	30	7	50	2	15
22	260	50	20	8	20	3	20
23	260	50	20	8	35	1	25
24	260	50	20	8	50	2	15
25	260	55	25	6	20	3	20
26	260	55	25	6	35	1	25
27	260	55	25	6	50	2	15

3.1.2 Experimental Result

Based on the Taguchi experimental design, all process parameters were set appropriately. Each experiment with a set of parameters was carried out and submitted to a lab for testing. Each specimen was brought together with a tensile test specimen and a flexural test specimen. Using a Type 1 tensile bar on a tensile test machine with a 5 kN load cell, the tests were conducted in accordance with ASTM D638. ASTM D790 was used to assess the flexural strength. Table 4 displays the tensile strength and flexural modulus results for each specimen.

Table 4
Results of tensile strength and flexural modulus

Experiment	Tensile strength results (kgf/cm^2)	Flexural modulus results (kgf/cm^2)
1	194.05	9573.67
2	191.10	9870.70
3	195.25	9716.47
4	193.17	9646.50
5	197.26	9875.88
6	196.45	9547.03
7	196.21	9716.55
8	196.43	10090.28
9	194.80	10083.18
10	188.57	9994.51
11	188.92	9587.74
12	189.44	9238.54
13	186.01	9714.82
14	188.41	9636.82
15	182.35	9842.94
16	190.97	9685.84
17	189.75	9782.20
18	188.48	9663.60
19	171.35	9313.63
20	165.01	9273.70
21	175.72	9206.43
22	172.52	9719.12
23	156.48	9194.24
24	170.62	9556.44
25	167.08	9295.73
26	155.33	9166.37
27	165.75	9525.45

3.1.3 S/N Analysis

The signal-to-noise (S/N) ratio was used to analyse the test findings. For tensile strength and flexural modulus, the S/N was determined by assuming that larger is better. This is to see how injection parameters affect certain quality aspects. Equations 1 to 6 show the S/N ratio formula. Table 5 shows the computed signal-to-noise ratio for both quality responses.

Table 5
S/N ratio for both responses

Experiment	Tensile strength results	Flexural modulus results	Tensile strength S/N ratio	Flexural modulus results
1	194.05	9573.67	45.76	79.62
2	191.10	9870.70	45.63	79.89
3	195.25	9716.47	45.81	79.75
4	193.17	9646.50	45.72	79.69
5	197.26	9875.88	45.90	79.89
6	196.45	9547.03	45.86	79.60
7	196.21	9716.55	45.85	79.75
8	196.43	10090.28	45.86	80.08
9	194.80	10083.18	45.79	80.07
10	188.57	9994.51	45.51	80.00
11	188.92	9587.74	45.57	79.63
12	189.44	9238.54	45.55	79.31
13	186.01	9714.82	45.39	79.75
14	188.41	9636.82	45.50	79.68
15	182.35	9842.94	45.22	79.86
16	190.97	9685.84	45.62	79.72
17	189.75	9782.20	45.56	79.81
18	188.48	9663.60	45.51	79.70
19	171.35	9313.63	44.68	79.38
20	165.01	9273.70	44.35	79.35
21	175.72	9206.43	44.90	79.28
22	172.52	9719.12	44.74	79.75
23	156.48	9194.24	44.53	79.27
24	170.62	9556.44	44.64	79.61
25	167.08	9295.73	44.46	79.37
26	155.33	9166.37	43.82	79.24
27	165.75	9525.45	44.39	79.58

3.1.4 S/N Analysis of tensile strength

By conducting a signal-to-noise analysis, the process parameter that has the most significant impact on both tensile strength and flexural modulus has been identified. The response table displays the delta rank, which ranks the process parameters from the most influential to the least influential for the selected quality characteristic. For the tensile strength quality characteristic, a "larger the better" signal was chosen. According to Table 6 and Figure 2, the most important parameter for achieving maximum tensile strength is the melt temperature, followed by holding time and then injection time, while injection speed has the least effect on tensile strength. The main effect plot for the S/N ratio illustrates the most effective process values for each selected process parameter. Based on the findings, the optimal injection moulding conditions for achieving maximum tensile strength were determined to be 180 °C barrel temperature, 7 seconds injection time, 2 seconds holding time, 20 seconds cooling time, 25 mm/s injection speed, 50 MPa holding pressure, and 35 MPa injection pressure.

Table 6
Signal to noise ratio of tensile strength

Level	Melting temperature	Injection pressure	Injection speed	Injection time	Holding pressure	Holding time	Cooling time
1	45.80	45.30	45.24	45.11	45.30	45.07	45.32
2	45.49	45.21	45.21	45.34	45.12	45.32	45.28
3	44.43	45.21	45.28	45.26	45.30	45.33	45.12
Delta	1.37	0.09	0.09	0.24	0.19	0.25	0.20
Rank	1	6	7	3	5	2	4

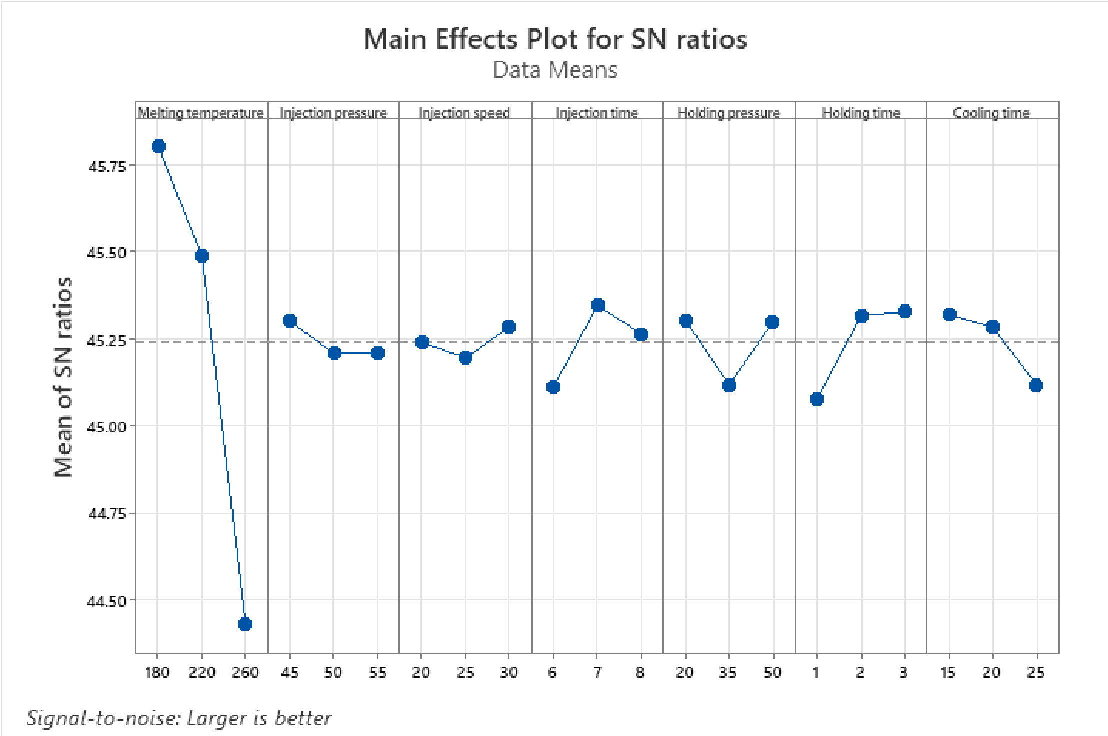

Fig. 2. Signal to noise ratio plot for compression strength

3.1.5 S/N Analysis of flexural modulus

The process parameter that had the most impact on flexural modulus was found to be the melt temperature, followed by holding time and then injection pressure. Table 7 and Figure 3 present the ranking of the influential parameters from most to least effective, with holding pressure being the least effective parameter for flexural modulus. Based on the findings, the optimal injection moulding conditions for achieving maximum flexural modulus were identified as 180 °C melt temperature, 2 seconds holding time, 55 MPa injection pressure, 8 seconds injection time, 30 mm/s injection speed, 20 seconds cooling time, and 20 MPa holding pressure.

Table 7
Signal to noise ratio of flexural modulus

Level	Melting temperature	Injection pressure	Injection speed	Injection time	Holding pressure	Holding time	Cooling time
1	79.82	79.82	79.58	79.68	79.64	79.53	79.63
2	79.72	79.72	79.68	79.59	79.60	79.75	79.69
3	79.43	79.43	79.70	79.69	79.72	79.67	79.64
Delta	0.39	0.12	0.10	0.12	0.03	0.22	0.07
Rank	1	3	5	4	7	2	6

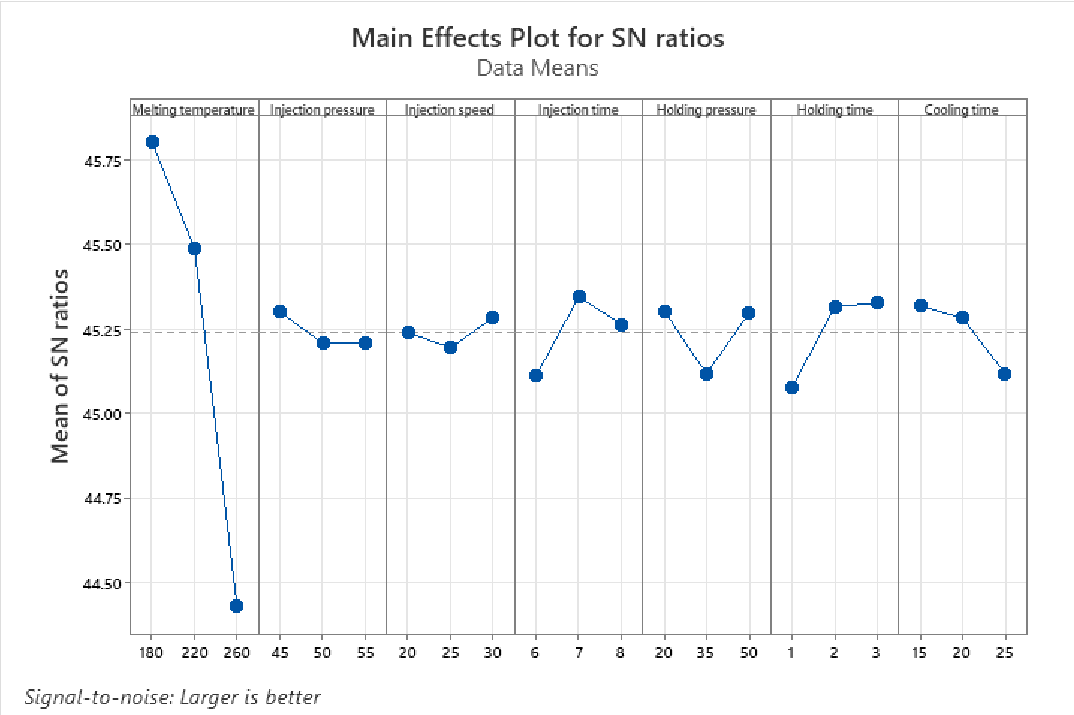

Fig. 3. Signal to noise ratio plot for flexural modulus

3.2 Parameter Optimisation
3.2.1 Desirability function

The desirability method is used to convert both tensile strength and flexural modulus into dimensionless values. This conversion allows the integration of both responses into a single dimensionless function called composite desirability. The composite desirability represents the overall desirability of the material. By evaluating the composite desirability, we can determine the most optimal value. The table 8 provided includes the individual desirability values for each response as well as the composite desirability.

Table 8
Desirability function of tensile strength and flexural modulus

Experiment	Tensile strength individual desirability	Flexural modulus desirability	Tensile and flexural composite
1	0.96	0.51	0.7
2	0.97	0.58	0.75
3	0.98	0.66	0.8
4	0.99	0.64	0.8
5	1	0.71	0.84
6	1	0.79	0.89
7	1	0.77	0.88
8	1	0.85	0.92
9	1	0.92	0.96
10	0.72	0.48	0.59
11	0.83	0.53	0.66
12	0.71	0.36	0.5
13	0.59	0.46	0.52
14	0.69	0.51	0.59
15	0.57	0.34	0.44
16	0.63	0.57	0.6
17	0.74	0.62	0.68
18	0.62	0.45	0.53
19	0.41	0.28	0.34
20	0.3	0.11	0.18
21	0.4	0.16	0.25
22	0.46	0.39	0.43
23	0.34	0.22	0.27
24	0.45	0.27	0.35
25	0.32	0.37	0.35
26	0.21	0.2	0.2
27	0.31	0.25	0.28

3.2.2 Multi-response optimisation

In this project, the optimisation of injection moulding parameters was conducted using multi-response optimisation techniques. The primary objectives were to enhance the tensile strength and flexural modulus of the moulded parts as well as optimise the overall performance using a composite desirability function. To achieve these goals, Minitab software, known for its advanced capabilities in multi-response optimisation, was employed. Through systematic variation and analysis of process parameters such as melting temperature, injection pressure, injection speed, injection time, holding pressure, holding time, and cooling time, as depicted in Figure 4, Minitab assisted in identifying the optimal combination of parameter values that maximised the tensile strength and flexural modulus of the moulded parts. Additionally, by integrating both responses into a composite desirability function, Minitab facilitated the determination of the optimal parameter values that maximised the overall performance. The use of Minitab software proved instrumental in systematically exploring the parameter space, analysing responses, and making informed decisions regarding parameter optimisation for injection moulding.

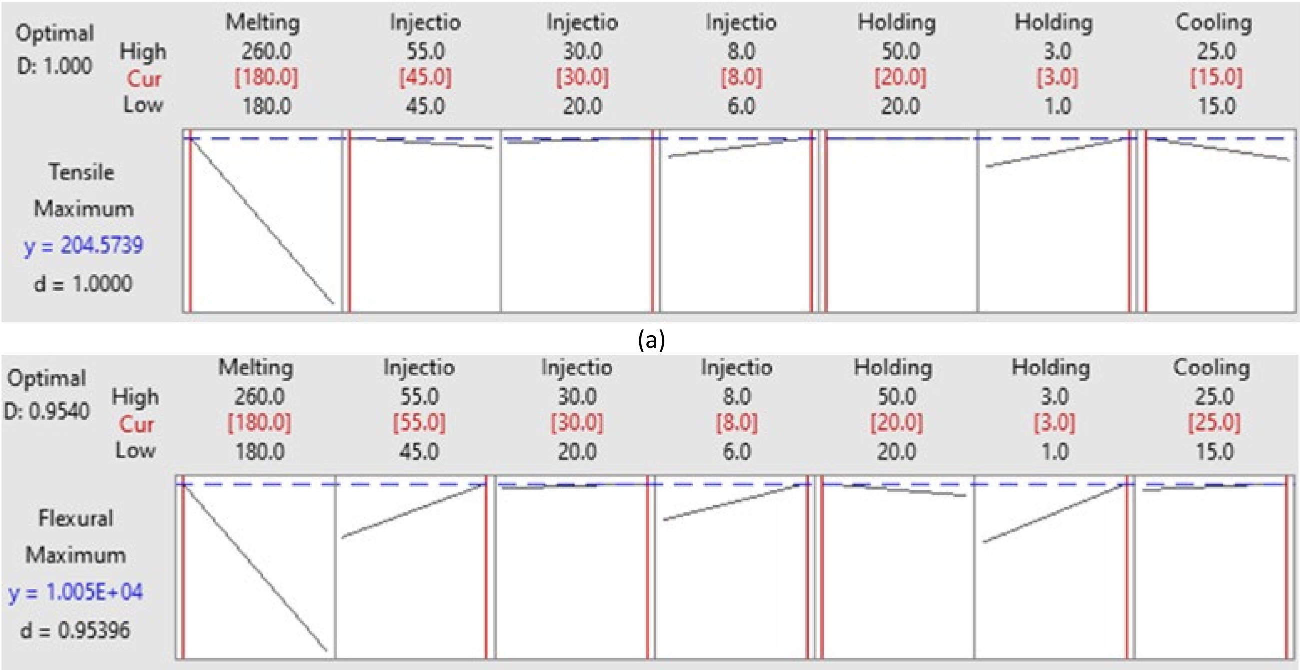

Fig. 4. (a) Tensile strength and (b) flexural modulus as responses for individual optimisation

3.2.3 Multi-response discussion

The results obtained from the Taguchi design of the experiment, the individual desirability function approach, and the composite desirability function approach may vary in terms of the optimal parameter values for each response variable. When optimising each response variable individually using the individual desirability function approach, it is expected to provide a better result for each specific response variable. When considering the tensile strength variable as a response, the optimal parameter values are identified as 180 °C melt temperature, 3 s holding time, 45 MPa injection pressure, 8 s injection time, 30 mm/s injection speed, 15 s cooling time, and 20 MPa holding pressure. However, when considering the flexural modulus as a response variable, the optimal parameter values might be different. On the other hand, the composite desirability function approach considers all the response variables as objective functions simultaneously. This method generates a single overall value for all the parameters of the algorithms, leading to an optimal value for all the response variables. It aims to find a balanced solution that optimises multiple responses collectively.

In summary, while optimising each response variable individually may provide better results for each specific variable, the optimal parameter values can differ. The composite desirability function approach, on the other hand, seeks to find a compromise solution that optimises multiple response variables simultaneously, resulting in an optimal value for all the response variables. The best set of process parameters for optimising part quality are: Melting temperature: 180°C, Injection pressure: 55 MPa, Injection speed: 30 mm/s, Injection time: 8s, Holding pressure: 20 MPa, Holding time: 3s, Cooling time: 25s With these parameter values, the tensile strength of the part is expected to be 199 kgf/cm^2, and the flexural modulus is expected to be 10050 kgf/cm^2. These values represent the optimised quality characteristics based on the chosen process parameters.

3.3 Conformation Test

To verify the estimated results obtained from the optimisation process, a confirmation test was conducted. This test aimed to validate the outcomes of Taguchi optimisation and assess the level of interaction effects between factors. However, determining a precise threshold for acceptable agreement between experimental and predicted values is challenging. The confirmation test involved using the optimal combination of process parameters on the same material and injection machine. The average values of tensile strength and flexural modulus were calculated. Table 9 presents a comparison between the average tensile strength and flexural modulus obtained from the confirmation experiment and the estimated values. This comparison serves to evaluate the agreement between the predicted and actual results based on the current set of parameters.

Table 9
Comparison between optimise value and the actual value

	Optimisation prediction	Actual result
Tensile strength	199 kgf/cm^2	190 kgf/cm^2
Flexural modulus	10050 kgf/cm^2	9875 kgf/cm^2

3.4 Quantitative Relationship between Process Parameters and Quality
3.4.1 Regression analysis

Regression analysis is a statistical technique used to examine the relationships between variables. In multiple linear regression analyses, the R-square value serves as a correlation coefficient and ideally falls between 0.8 and 1, according to [23]. The purpose of the R-squared value is to predict future outcomes based on related data, providing an indication of how well the model can predict results accurately. In this study, a linear model was developed to explore the relationship between injection moulding parameters and quality characteristics. To assess the model's performance, the regression coefficient values and R-square values were examined. A higher R-Square value closer to 1.00 indicates a better fit of the model to the data. Utilising utilisable orange software, the analysis was conducted, and the results of the regression coefficients for tensile strength and flexural modulus can be found in Tables 10 and Table 11, respectively.

Table 10
Coefficient of tensile strength

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	258.867	17.0	14.89	0.000	-
Melting temperature	-0.354	0.0280	-12.04	0.000	1.00
Injection pressure	-0.162	0.224	-0.77	0.449	1.00
Injection speed	0.0079	0.224	-0.24	0.810	1.00
Injection time	1.592	1.12	2.07	0.053	1.00
Holding pressure	-0.004	0.0747	-0.05	0.959	1.00
Holding time	2.445	1.12	1.64	0.118	1.00
Cooling time	-0.374	0.224	-1.13	0.274	1.00
Model	MSE	RMSE	MAE	R^2	
Linear regression	19.986	4.471	3.481	0.878	

Table 11
Coefficient of flexural modulus

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	9603	735	13.07	0.000	-
Melting temperature	-5.37	1.21	-4.44	0.000	1.00
Injection pressure	13.71	9.69	1.42	0.173	1.00
Injection speed	1.29	9.69	0.13	0.895	1.00
Injection time	46.5	48.4	0.96	0.349	1.00
Holding pressure	-1.04	3.23	-0.32	0.751	1.00
Holding time	75.9	48.4	1.57	0.134	1.00
Cooling time	1.60	9.69	0.17	0.870	1.00
Model	MSE	RMSE	MAE	R^2	
Linear regression	29704.805	172.351	139.187	0.570	

3.4.2 Feasibility Studies

Upon comparing the optimised process parameters with the initial parameters prior to optimisation, a slight improvement in both tensile strength and flexural modulus can be observed. Specifically, there is an increase in both tensile strength and flexural modulus values. Despite the relatively small magnitude of these changes, they have a significant impact on the quality output of the product.

A comparison was made between the mechanical properties of virgin polypropylene and recycled polypropylene. The results, depicted in Figures 5(a) and 5(b), indicate a slight improvement in strength when the optimised process parameters are compared to the master parameters. It should be noted that achieving recycled plastic parts with mechanical properties equivalent to those of virgin plastic is not possible. However, by carefully controlling all significant processing parameters during the manufacturing process, it is feasible to identify the optimal range of mechanical properties for these recycled materials. The graphs below, Figures 5(a) and 5(b), illustrate the comparison between the results after optimisation, the results before optimisation, and the properties of virgin material.

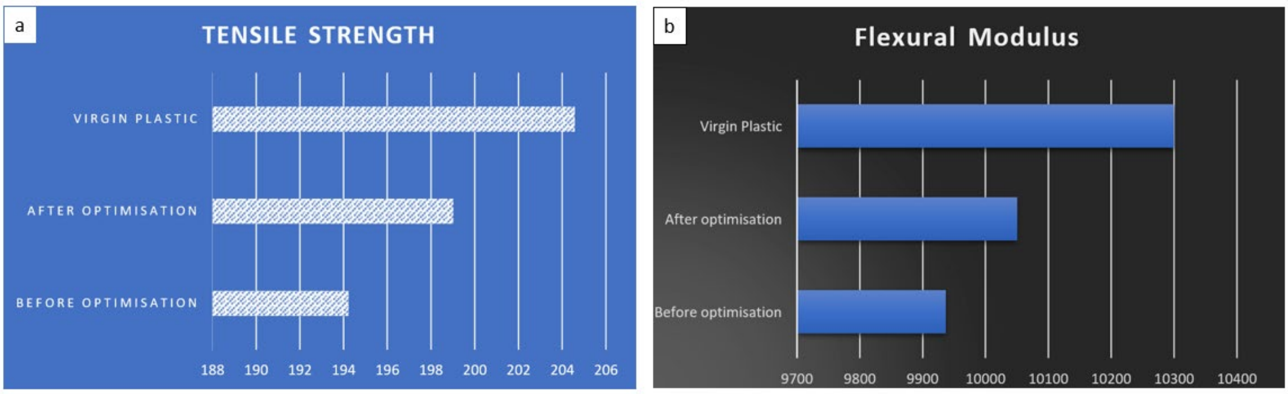

Fig. 5. (a) Tensile strength and (b) flexural modulus as comparisons before and after optimisation

4. Conclusions

This study investigates the optimal injection moulding process parameters for recycled polypropylene, focusing on tensile strength and flexural modulus. Seven parameters were chosen: melt temperature, injection pressure, injection speed, injection time, holding pressure, holding time, and cooling time. Preliminary testing was conducted to determine the values for each parameter. The results were used to optimise the process parameters using Taguchi methods and desirability functions. The analysis revealed that melt temperature, injection time, and holding time are the most influential factors affecting maximum tensile strength. For flexural modulus, melt temperature, holding time, and injection pressure were the most influential, while holding pressure had the least impact.

The integration of desirability functions and Taguchi methods was necessary to optimise multiple responses. The best set of process parameters was determined as 180°C melt temperature, 55 MPa injection pressure, 30 mm/s injection speed, 8 s injection time, 20 MPa holding pressure, 3 s holding time, and 25 s cooling time. These parameters predicted part quality with a tensile strength of 199 kgf/cm^2 and a flexural modulus of 10,050 kgf/cm^2. A confirmation test was conducted to verify the results and assess the presence of interaction effects between factors. The regression analysis showed a quantitative relationship between the process parameters and product quality, with an R-square of 85% for tensile strength and 59% for flexural modulus, indicating that the process factors explain 85% of the differences in tensile strength and 59% of the differences in flexural modulus.

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