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THE INFLUENCE OF TEMPERATURE AND SCREW ROTATION SPEED ON DIAMETER IRREGULARITY IN PLASTIC EXTRUSION USING RECYCLED PLA

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ABSTRACT
This research investigates the effect of extrusion temperature and screw rotation speed on the diameter irregularity of filaments produced from recycled polylactic acid (PLA) using a single screw plastic extruder. The study addresses the growing demand for sustainable 3D printing materials by reprocessing failed or unused PLA prints into usable filament. Experimental variables included three temperature settings (150°C, 160°C, and 170°C) and three screw rotation speeds (20 rpm, 30 rpm, and 40 rpm), producing a total of 360 diameter measurements. The results show that both temperature and screw rotation speed significantly influence diameter consistency, with screw speed having a more dominant effect. The optimal condition for achieving the target filament diameter of 1.75 mm was found at 170°C and 40 rpm, yielding a predicted diameter of 1.7378 mm with a desirability score of 0.97888. These findings confirm the potential of recycled PLA as a viable material for consistent filament production when proper extrusion parameters are applied. The test was done by using minitab software to aid the research analysis.

Keywords : *Recycled PLA, Extrusion, Screw Rotation Speed,, Temperature, Filament, 3D Printing*

1. Introduction

Plastics are used in various fields of life such as packaging, transportation, building materials, electronic components, and consumer products. The high demand for plastic causes an increase in plastic production in the world. However, most plastic are only used in short time and then discarded. This plastic waste then contaminates almost all parts of the world and becomes a global problem[1].

However, plastic becomes one of the environmental issues in the world because some people have not been able to use it wisely. Plastic is also extremely dangerous for the ocean because plastic rubbish goes all the way to the sea for last destination. The impact is a hazard to marine life. Million tons of plastic garbage are currently entering to the ocean every year from land through river mostly located in Asia. On the other impact of plastic waste, it affects the condition on coral reefs which increase diseases that can threaten them[2]. This issue can be destructive to the earth if ot dealt with using all means available to us.

3D printing, also known as additive manufacturing (AM), is a manufacturing technology that is commonly regarded as a sustainable manufacturing method. Compared to traditional subtractive method, 3D printing demonstrated the potential to reduce waste, energy demand, and carbon emissions[3].

In recent time, polylactic acid (PLA) has emerged as a preeminent raw material employed in fused deposit modelling (FDM) based 3D printing process, due to its biodegradability and eco-friendly attributes. Therefore, integrating 3D printing and recycling can play crucial role in reducing waste and promoting the principles of circular economy. As a consequence, to enhance the sustainability of 3D printing, it is crucial that the printer utilize sustainable feedstock[3]. This highlights the importance of developing efficient recycling and extrusion methods for PLA to maintain its material integrity, as repeated processing may affect its mechanical performance.

A significant consideration in recycling polylactic acid (PLA) for filament applications is its rate of biodegradation. Although PLA is classified as a biodegradable polymer, its degradation process in a natural environment is notably slow. For instance, studies have shown that over a 150-day period, the tensile strength of PLA decreases by 40.1%, while its impact energy is reduced by only half of its initial value. This mechanical degradation can accelerate the subsequent biodegradation rate, as the breakdown of the polymer's chemical chains makes them more accessible to microorganisms. However, considering the high demand for PLA, this extended degradation timeframe can lead to environmental concerns[4]. The 40.1% drop in tensile strength over 150 days and the halving of its impact energy show that mechanical properties degrade faster than the material itself. This early mechanical weakening might actually help the biodegradation process by making it easier for microbes to break down the polymer chains. However, since PLA is being used more and more, especially in 3D printing, the slow natural breakdown still presents an environmental issue that needs to be addressed.

2. Literature Review

Research conducted by Aly and colleagues in 2024 about investigation of mechanical properties of 3D printing filament using blends of virgin and recycled polylactic acid (PLA) highlighting the importance of proper feedstock preparation and suggest optimizing extrusion process to improve filament quality. The method used includes mixing crushed recycled PLA with virgin PLA, followed by an extrusion process using a single-screw extruder and printing specimens using a Creality CR-10 printer. Heating temperature for all specimen in this experiment are using 4 heaters with different temperature ranged from 170°-190°C with a fan for cooling device. The desired filament diameter is set to 1.74 mm, closely matching the commercially available filaments that is 1.75 mm. After printing, the specimens were tested using tensile testing and strain distribution analysis via Digital Image Correlation (DIC). The results showed that 100% virgin PLA have 12.80 MPa of yield strength, 20.58 MPa of ultimate tensile strength, 5.86 GPa of modulus, 6.75% of ductility, and 101.13 J/m³ of toughness while 100% recycle PLA results showed 13.10 MPa of yield strength, 20.31 MPa of ultimate tensile strength, 6.08 GPa of modulus, 6.17% of ductility, and 89.96 J/m³ of toughness[5]. From this research, it can be seen that recycled PLA still shows comparable mechanical properties to virgin PLA, even slightly higher in terms of yield strength and modulus. Although there is a slight drop in ultimate tensile strength, ductility, and toughness, the differences are relatively small. This indicates that with proper feedstock preparation and controlled extrusion parameters, recycled PLA can still be a reliable material for 3D printing. It also shows that optimizing the process, rather than relying solely on virgin material, can support sustainability without significantly compromising performance.

PLA is a biopolymer that is created by extracting monomer from nontoxic renewable agricultural sources that can decreasing carbon emission, with melting point of PLA is from 160°-180°C. Making the PLA is one of the most promising biopolymers in the market[6]. Considering its renewable origin and low environmental impact, PLA stands out as a strong candidate for sustainable manufacturing. Additionally, its low melting point makes it easier to process, which is ideal for 3D printing. These characteristics explain why PLA continues to gain traction as one of the leading biopolymer materials in the industry.

In research conducted by Ponsar in 2020, about analysis of fluctuation in extrusion machine on 3D printing filament quality. This research referring to analysis of process for filament fabrication using mixture of ethyl cellulose and hypromellose with parameter that influence the diameter inconsistencies. The diameter of extruded filament is influenced by various parameters, particularly powder feed rate (PFR). Variation in diameter can also be attributed to changes in material pressure, which is affected by PFR and screw rotation speed. Fluctuation in material pressure cause pulsating transport of the melt, resulting in diameter inconsistencies, rotation speed at 20 rpm, 30 rpm, and 40 rpm have necessary build up pressure to push the melt making and lowering diameter variation, with 20 rpm give the best diameter consistency and above 40 rpm have more fluctuation on the diameter[7].

In research conducted by Herianto in 2020, about parameter optimization for extrusion process using recycled polypropylene. In order to address the global plastic waste problem and make the printing process more ecologically friendly, the research focuses on optimizing the extrusion process parameters for creating recycled polypropylene filaments meant for 3D printing ideally close to 1.75 mm of filament diameter and tolerance standard of 0.05 mm. To examine important variables like temperature, spooler speed, and extrusion speed, the researchers used Taguchi and ANOVA techniques. The ideal parameters were found to be a spooler speed of 4 rpm, an extrusion speed of 40 rpm, and an extrusion temperature of 200°C. The generated filaments, however, had uneven and readily curved surfaces, underscoring the necessity for additional study to improve the filament's surface quality with the variable of screw speed of the experiment are 40 rpm and 50 rpm[1]. Screw rotation speed plays a crucial role in determining the consistency of filament diameter during extrusion. Lower speeds tend to produce more stable pressure and smoother melt flow, which helps minimize diameter fluctuation. By selecting 20, 30, and 40 rpm, this study aims to evaluate how gradual increases in screw speed affect melt behavior and dimensional stability.

Temperature has a big effect on the plastic extrusion process because it changes how easily the polymer flows. When the temperature increases, the viscosity (or thickness) of the melted plastic decreases, making it flow more smoothly through the machine. This means less force is needed to push the material, and the product comes out more consistently[8]. Temperature affects how easily the polymer flows during extrusion. Higher temperatures reduce viscosity, making the material flow more smoothly and improving consistency.

Screw rotation speed, typically measured in revolutions per minute (rpm), refers to how fast the screw inside the extruder turns to move and pressurize the molten plastic through the barrel and die. This parameter directly influences the shear rate experienced by the polymer melt. As the screw rotation speed increases, more melted plastic is pushed out, which can make the filament diameter larger if the pulling speed or cooling is not adjusted[9]. Higher screw rpm increases the shear rate, which not only pushes more molten plastic through the die but also reduces the melt viscosity, making the flow easier.

With self-produce machine, there will need a parameter for each material that will be processed, the parameter will affect the filament for 3D printing quality. Parameters for 3D printing filament such as, heating temperature and screw rotation speed will influence diameter for the product of plastic extrusion machine that ultimately will impact the production of 3D printing machine. The result of this research expected to give a brief guide to optimize the quality of 3D printing filament.

3. Research Methods

The material used in this study was recycled polylactic acid (PLA) sourced from failed or unused 3D printing parts. The PLA was manually cleaned and shredded into approximately 5 mm pieces in **Figure 1** using a mechanical shredder. The extrusion process utilized a single screw plastic extruder equipped with a 1.75 mm diameter nozzle shown in **Figure 2**. A vernier caliper with a precision of 0.01 mm was used for filament diameter measurement. No active cooling system was applied during filament extrusion. The machine that is used in here is also a self-made machine that uses 3 phase motor with 1HP of power output that is integrated with inverter that can be used to set the screw rotation speed by changing the electrical frequency.

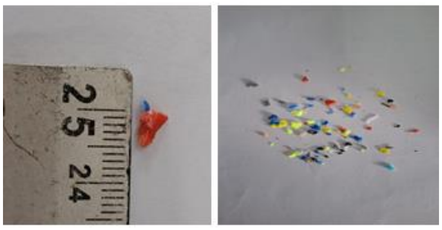

Figure 1. Shredded PLA Plastic

Figure 2. Single Screw Plastic Extruder Machine (used for this research)

This research used an experimental approach to examine the effect of extrusion temperature and screw rotation speed on the dimensional consistency of recycled PLA filament. The experiment was conducted at the State Polytechnic of Malang. Three temperature settings were applied: 150°C, 160°C, and 170°C. Additionally, three screw rotation speeds were tested: 20 rpm, 30 rpm, and 40 rpm, the variable can be seen in **Table 1**. For each combination of temperature and screw speed, four repetitions of filament samples were produced. Each filament was measured ten times, with measurements taken every 10 cm along its length. The goal was to analyze the variation in filament diameter and identify parameter settings that produce consistent results. The software that used to aid this research is by using minitab. There are few analysis that will be held are: two-way ANOVA, main effect plot, interaction plot, and response optimization, all of these analytical tool will help us to understand better of how this research will carried us into. The result of the analysis will later discuss and concluded thus will give us insight to the research that has been held and may be useful for further research.

Table 1 - Research Variables

	Temperature	Screw Rotation Speed
1	150°C	20 rpm
2	160°C	30 rpm
3	170°C	40 rpm

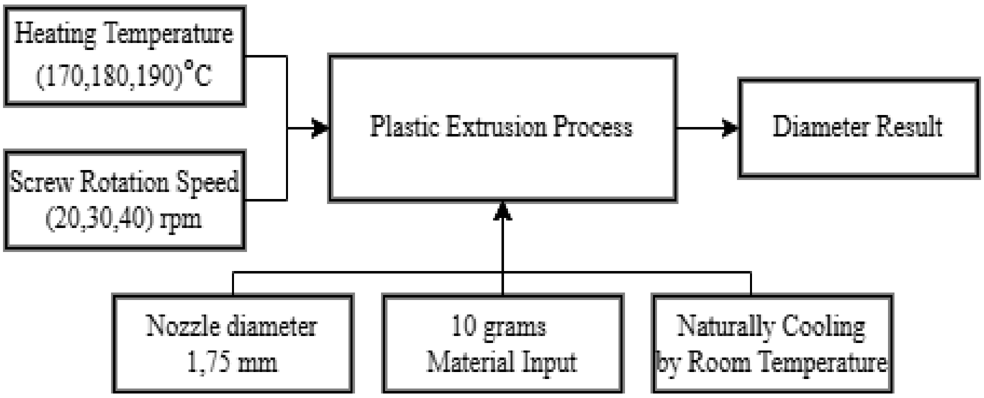

Figure 3. Research Framework

The research Framework that shown at **Figure 3** will help to understand better of how this method and materials in this research work.

Temperature of melting point of PLA by 160°-180°C [6] and temperature at 170°-190°C [5] was experimented and the result for the extruded PLA at temperature 180°C is too molten , thus cannot be produced in filament form. Further experiment showed that the highest temperature that can produce PLA in filament form with this machine that has no cooling device for the extruded material is at 170°C, while the lowest temperature is 150°C. Temperature lower than 150°C will resulting in bad form of extruded filament or cannot be extruded at all due to the PLA has not melt.

Screw rotation speed also has been tested with the reference of 20, 30, and 40 rpm using mixture of ethyl cellulose and hypromellose [7] and screw rotation speed at 40 rpm and 500 rpm using recycled polypropylene [1] was showing the best shaped filament for this research is from 20 – 40 rpm while at above 40 rpm the filament will be deformed due to excess pressure from the screw.

In conclusion this is how the author choose the temperature of 150°C, 160°C, and 170°C with the screw rotation speed using 20 rpm, 30 rpm, and 40 rpm for extruding using recycled PLA plastic with the single screw plastic extruder machine.

4. Results and Discussions

This section presents the experimental results and discusses the influence of temperature and screw rotation speed on the filament diameter produced from recycled PLA. A total of 360 measurements were obtained by producing four filaments for each combination of variables, with each filament measured at 10 points along its length at 10 cm intervals. The data of mean diameter of every 4 replication per each pair of variances will be shown in **Table 2**. Data that showed here only the mean value or average value that are measured in 4 replicates of filament for each pair of variables. There is more fluctuation that can be shown with the raw data, but we can use the table and graph from analytical tool to see the raw data that has been calculated throughout.

Table 2 - Measurement Data

Temperature (°C)	Rotation Speed (rpm)	Diameter (mm)									
		1	2	3	4	5	6	7	8	9	10
150	20	1,54	1,47	1,50	1,54	1,48	1,54	1,53	1,38	1,45	1,41
	30	1,50	1,51	1,49	1,42	1,39	1,37	1,41	1,38	1,33	1,37
	40	1,63	1,64	1,72	1,51	1,56	1,53	1,46	1,44	1,51	1,42
160	20	1,55	1,50	1,52	1,55	1,52	1,59	1,47	1,48	1,50	1,51
	30	1,55	1,56	1,48	1,54	1,56	1,56	1,54	1,58	1,53	1,53
	40	1,69	1,70	1,77	1,75	1,70	1,75	1,69	1,71	1,68	1,63
170	20	1,33	1,24	1,27	1,36	1,27	1,30	1,29	1,29	1,17	1,28
	30	1,51	1,59	1,61	1,70	1,56	1,57	1,49	1,52	1,54	1,48
	40	1,65	1,72	1,76	1,82	1,83	1,70	1,75	1,73	1,74	1,69

Table 3 - Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Temperature	2	0,7093	0,35465	11,34	0,000
Screw Rotation Speed	2	3,419	1,70951	54,68	0,000
Error	355	11,0986	0,03126		
Lack-of-Fit	4	1,9824	0,4956	19,08	0,000
Pure Error	351	9,1162	0,02597		
Total	359	15,2269			

Based on the results of the Analysis of Variance shown in **Table 3**, It is found that both temperature and screw rotation speed significantly influence the diameter irregularity of the filament produced using a single screw plastic extruder with recycled PLA material. This is supported by the P-values of both factors, which are 0.000, indicating that their effects are statistically significant. These results suggest that optimizing screw rotation speed plays a key role in minimizing diameter irregularity and improving the quality of recycled PLA filament in the extrusion process.

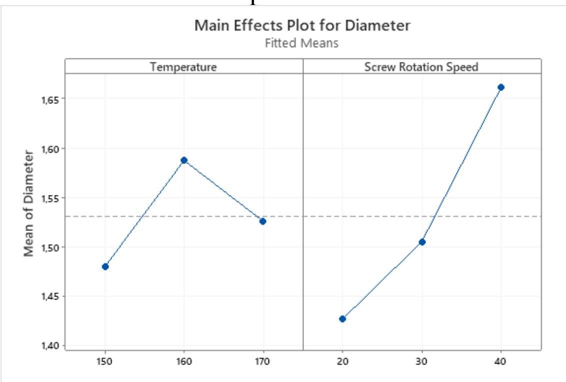

Figure 4. Main Effect Plot

The main effects plot for diameter like the one that shown in **Figure 4.** illustrates the individual influence of temperature and screw rotation speed on the mean diameter of the filament produced. It is important to note that this plot displays the main effects of each factor independently, without accounting for any interaction between them.

From the plot of **Figure 4**, it can be seen that the mean diameter increases as temperature rises from 150°C to 160°C, reaching its highest point at 160°C. However, when the temperature increases further to 170°C, the mean diameter decreases slightly.

For screw rotation speed, the plot shows a clear and consistent upward trend: as the speed increases from 20 to 40 rpm, the mean diameter also increases, with the highest value at 40 rpm. However, since this plot does not consider the combined influence of temperature and screw speed, further analysis using an interaction plot is necessary to fully understand how these two variables work together to affect filament quality.

Both of the plot from main effect plot showed us that both of temperature and screw rotation speed have a certain point to achieve the targeted value which are: 160°C and 40 rpm. But the plot only analysing the individual variable thus, further analysis from interaction plot is needed.

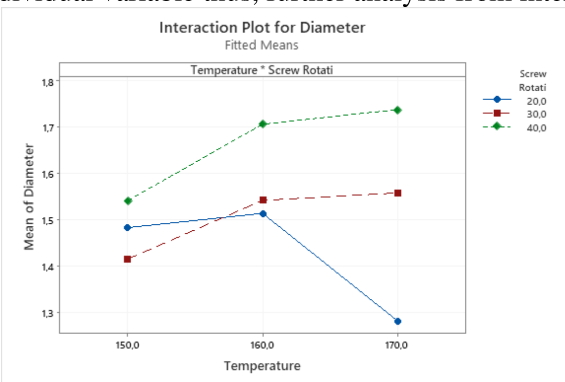

Figure 5. Interaction Plot

The interaction plot like shown in **Figure 5** for diameter illustrates how the combination of temperature and screw rotation speed influences the mean filament diameter. This allows for a more complete understanding of the relationship between variables in the extrusion process by analysing bot of variable at the same time unlike the main effect plot.

From the plot in **Figure 5**, it can be observed that the lines representing different screw rotation speeds are not parallel, indicating a clear interaction between temperature and screw rotation speed. At a screw rotation speed of 20 rpm (blue line), the filament diameter remains relatively stable between 150°C and 160°C but drops significantly at 170°C. In contrast, at 30 RPM (red dashed line), the diameter increases slightly with temperature and then plateaus between 160°C and 170°C. At 40 rpm (green dashed line), the diameter consistently increases with temperature and reaches its highest value at 170°C.

This interaction suggests that the optimal temperature for achieving a consistent diameter may depend on the selected screw speed. For example, while 160°C may appear ideal at lower speeds, higher temperatures such as 170°C yield better results when paired with higher screw speeds like 40 rpm.

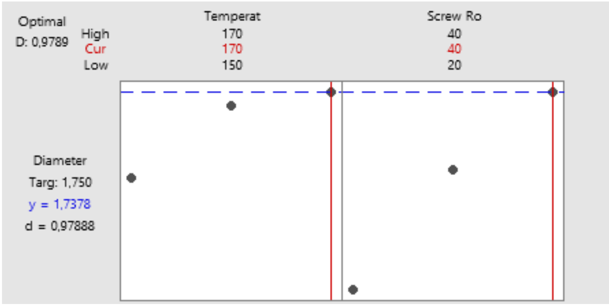

Figure 6. Response Optimization

Based on the optimization plot that shown in **Figure 6**, the ideal combination of temperature and screw rotation speed for achieving the target filament diameter is 170°C and 40 RPM, respectively. The plot shows that the predicted mean diameter under these conditions is 1.7378 mm, which is very close to the desired target of 1.750 mm. This near-optimal result is further supported by a high desirability value of 0.97888, indicating that the selected parameters are highly effective in meeting the dimensional target. These results demonstrate that optimizing both factors simultaneously is crucial for improving the dimensional accuracy and quality of recycled PLA filament in the extrusion process

Table 4 - S Value data

Temperature (°C)	Screw Speed (rpm)	S Value
150	20	0,2061
150	30	0,2579
150	40	0,1468
160	20	0,1791
160	30	0,1004
160	40	0,138
170	20	0,1699
170	30	0,1463
170	40	0,0852

To analyze the diameter irregularity of the filament, we will review the S data value from each of the nine combinations of heating temperature (150°C, 160°C, and 170°C) and screw rotation speeds (20, 30, and 40 rpm). From these control charts, we can focus on the standard deviation since it directly represents the consistency or irregularity of filament diameter.

At 150°C and 20 rpm, the process shows moderate variability ($\bar{S}$ = 0.2061). Although it's within control limits, there are small fluctuations that indicate some instability. As screw speed increased to 30 rpm, the variation also increased slightly ($\bar{S}$ = 0.2579), and though it remained stable, this higher deviation suggests the diameter becomes slightly more inconsistent. Interestingly, when the speed was raised to 40 rpm at the same temperature, the variation dropped significantly ($\bar{S}$ = 0.1468). This suggests that higher screw speed at low temperature improves consistency, possibly because the material is being pushed more uniformly despite lower melt flow at 150°C.

At 160°C and 20 rpm, the S chart indicates a lower deviation (S = 0.1791) compared to 150°C at the same speed, suggesting that higher temperature helps smooth the extrusion. This trend improves further at 30 rpm, where the variation drops to $\bar{S}$ = 0.1004, making this one of the most consistent results. This is likely due to optimal balance: the polymer is melted well, and the screw speed supports a steady flow. However, increasing to 40 rpm unexpectedly leads to a higher variation ($\bar{S}$ = 0.1380), though still lower than at 150°C. This may be due to excessive shear or turbulence in the melt at higher speeds combined with higher viscosity reduction at this temperature.

At 170°C, we observe more mixed results. At 20 rpm, the variation is moderate ($\bar{S}$ = 0.1699), but not the best. Increasing the screw speed to 30 rpm gives similar results to 160°C 40 rpm, with $\bar{S}$ = 0.1463 relatively stable but not ideal. The most notable result is at 170°C and 40 rpm, where the S value is the lowest ($\bar{S}$ = 0.0852). This is the most consistent diameter of all settings tested, suggesting that the polymer flow is highly stable at this temperature and speed. Likely, the high temperature reduces the viscosity significantly, allowing the material to flow smoothly, and the higher screw speed ensures uniform feeding without pulsation or fluctuation.

In summary of how the heating temperature effecting the diameter irregularity. Temperature plays a crucial role in determining the melt quality of the PLA and how uniformly it can be extruded. At 150°C, the PLA may not be fully melted, leading to a more viscous flow. This condition can cause fluctuating pressure at the nozzle and result in more inconsistent filament diameters. This is reflected in the higher $\bar{S}$ values seen at 150°C, especially at 30 rpm ($\bar{S}$ = 0.2579), which is the highest among all conditions tested. As the temperature increases to 160°C, the melt becomes more uniform, leading to smoother flow and improved diameter consistency. This improvement is evident at 160°C and 30 rpm, where the S value drops significantly to 0.1004, suggesting that this is a more stable extrusion setting. At 170°C, the material becomes even more fluid, reducing internal resistance and allowing for very stable flow. This results in the lowest overall $\bar{S}$ value of 0.0852 at 40 rpm, showing that higher temperatures can enhance diameter regularity when properly balanced with screw speed. However, too high a temperature at low speeds (170°C and 20 rpm) may cause slight inconsistencies due to polymer degradation or excessive softening.

In summary for how the screw rotation speed can impact the diameter irregularity will be discussed. Screw rotation speed influences how consistently the melted PLA is pushed through the nozzle. At a low speed of 20 rpm, the flow rate is slower and may be more prone to pressure fluctuations or pulsation, especially if the material is not completely melted. This is seen in moderate $\bar{S}$ values such as $\bar{S}$ = 0.2061 at 150°C and $\bar{S}$ = 0.1699 at 170°C. Increasing the speed to 30 rpm generally improves pressure stability and feeding consistency. However, this setting shows variable outcomes depending on the melt quality, good regularity at 160°C $\bar{S}$ = 0.1004) but poor at 150°C ($\bar{S}$ = 0.2579), due to incomplete melting. At 40 rpm, the screw provides more continuous pressure and reduces fluctuation in feeding. This is especially effective at higher temperatures. For example, at 160°C and 40 rpm, the S value is 0.1380, and at 170°C and 40 rpm, the $\bar{S}$ value drops further to 0.0852, the best result overall. The higher screw speed likely maintains consistent flow, especially when the PLA is properly melted. This shows that 40 rpm consistently results in lower S values compared to 20 and 30 rpm, making it the optimal setting for achieving diameter consistency.

5. Conclusion

This study aimed to evaluate the effects of extrusion temperature and screw rotation speed on the diameter irregularity of filament produced using recycled PLA material in a single screw plastic extruder. Through systematic experimentation and statistical analysis, valuable insights were obtained regarding the process parameters that influence filament dimensional stability. The following key conclusions were drawn from the study:

1. The result of this research shows that heating temperature has a significant effect on the diameter irregularity of recycled PLA filament. At lower temperature like 150°C, the material is not fully melted, causing unstable flow and resulting in higher diameter variation, which is shown by high $\bar{S}$ value such as 0.2579 at 150°C and 30 rpm. As the temperature increases to 160°C and 170°C, the PLA melts more evenly, reducing viscosity fluctuation and improving flow stability. This condition makes the filament diameter more consistent, as seen from lower $\bar{S}$ values like 0.1004 at 160°C and 0.0852 at 170°C. Therefore, increasing temperature improves diameter regularity up to a certain point, and the best temperature for stable filament diameter is 170°C.

2. The screw rotation speed also affects the filament diameter consistency significantly. At low speed like 20 rpm, the flow of the melt is slower and more unstable, which causes diameter fluctuation as shown with $\bar{S}$ values around 0.1699 to 0.2061. As the speed increases to 30 rpm, the effect depends more on how well the material is melted, with mixed results. However, at 40 rpm, the screw consistently pushes the material with more uniform pressure, producing more stable diameter. This is proven by the lowest $\bar{S}$ value of 0.0852 found at 40 rpm and 170°C. From this result, it can be concluded that higher screw speed (40 rpm) is more effective to reduce diameter irregularity and improve filament quality.

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