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Investigating the effect of dishwasher on 3D printed food-contact material

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ABSTRACT

The purpose of this study was to explore the dishwasher exposure effects on bacterial reduction, mechanical properties, and heat deflection temperature (HDT) of 3D printed food-contact material objects (FCMs) fabricated from Polymaker PETG and NonOilen filaments which can get in contact with food materials. Samples were subjected to hand washing as simulation of the well-known everyday kitchen cleaning procedure and regular dishwasher cycles for bacterial reduction. The efficiency of the bacterial reduction was tested by comparing microbial performance between samples that received hand washing and samples cleaned by the dishwasher, the results indicating that the treatment of dishwasher was superior in reducing bacterial load. Mechanical property evaluations (tensile strength, layer adhesion, bending and impact resistances) and HDT were carried out for samples subjected to dishwasher cycles and compared with the non-washed as the control samples. The results revealed a significant impact of the dishwasher on the mechanical properties and the HDT with respect to both materials: Polymaker PETG and NonOilen.

KEYWORDS

3D printing, microbial safety, mechanical properties, heat deflection temperature, dishwasher

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1. INTRODUCTION

Additive manufacturing technology has proven to be very promising as rapid prototyping in the manufacturing zone. This technology has been significantly modified and gradually developed into a useful device in research, manufacture, engineering and science fields. Design, manufacturing, electronics, materials and business sectors working together in single package created a three-dimensional (3D) printer (Kamran, 2016). 3D printing is also known as additive manufacturing, a technology that uses consecutive layers of material to create real objects from a geometric representation. 3D printing technique involves computer-aided design (CAD) to structure a 3D object in its physical configuration from its digital form (Lee et al., 2019).

Nowadays, due to the rising number of users the complexity and multi-functionality of products have led to the discovery of advanced materials, including nano materials, functional materials, biomaterials, smart materials and fast drying concrete, which are suitable for 3D printing and serve as feed materials for the production of practical objects (Rong et al., 2023). Fussed deposition modelling (FDM) is an extrusion-based three-dimensional printing process, which is commonly used in the various industries (Crisostomo and Dizon, 2021). FDM makes use of thermoplastic polymers that are heated above their melting point in the printhead and then extruded from a nozzle on a moveable printer table layer by layer thanks to the pressure of the filament fed into the printhead (De Leon et al., 2016). FDM technology is characterized by less complexity and the easily obtainable raw materials (filaments). The frequently used polymers in the FDM methods are: Amorphous acrylonitrile-butadiene-styrene polymer (ABS) (Pakuła et al., 2022), polyethylene terephthalate (PET) (Tanikella et al., 2017), glycol-modified poly ethylene terephthalate (PET-G) (Pakuła et al., 2022), polyamide 12 (PA12) (Kam et al., 2023), polylactic acid (PLA) (Pakuła et al., 2022) and, biodegradable NonOilen (Horv et al., 2024).

For food safe 3D printing materials intended for food contact it is vital to ensure compliance with regulatory standards such as FDA CFR 21 in the United States and EU Regulation 10/2011 in Europe. According to FDA CFR 21, Part 177, materials that are used in food packaging or utensils must be thoroughly tested to ensure they do not leach unwanted substances into food (U.S. Food and Drug Administration, 2021). Similarly, EU Regulation 10/2011 specifies specific migration limits and requires approval for any substance used in food-contact plastics within the European Union (European Commission, 2011).

The cleaning and decontamination of the 3D printed parts and tools are important in ensuring their long-term safe use. 3D printed objects made from various polymers should be cleaned to the required levels that are safe for medical and food applications. The area between the layers of 3D printed objects, or dimples, poses the greatest risk to creating food-safe or washable products. Bacteria can thrive and replicate in narrow areas, making cleaning difficult. The average bacterium from food poisoning measures 1.5–5.5 μm in length and 0.25–1.75 μm in diameter (Khamisse et al., 2012). Proper washing solution and washing duration ensure the biocompatibility of printed components by removing superfluous resin on the surface of the printed product (Hwangbo et al., 2021), although the long washing duration of the sample may have detrimental effects on the mechanical properties and surface quality of the specimen because of the absorption of the solvent into the surface, resulting in plasticizing effects. In addition, extreme post-curing may cause brittleness, the breaking of polymers into simple form, and inferior material properties (Hassanpour et al., 2024).

There are several consumer operations, such automatic dishwashers (ADWs), where chemical engineering methodologies can be effective in moving beyond the existing semi-empirical approach. The normal cleaning procedure for an automatic dishwasher typically involves several rinse stages followed by the main washing cycle, during which detergent is released from a compartment—usually triggered by a change in temperature or the timing of the cycle. Principles would include washing and drying many items within the shortest possible time, while also minimizing water and energy. ADW's performance measures show that it saves over 75% of the water and 25% of the energy compared to hand washing a standardized load. However, the ultimate outcomes are dependent on the user, the type of things distributed, the area covered by water, the physical energy provided (depending on the appliance design), and the performance of the formulated detergent that has been employed (Letzelter and Bakalis, 2017).

In fact, the credit for inventing a dishwasher is mostly given to Josephine Cochrane, who, in 1886, patented a manual-driven device that washed dishes. The most interesting point in it is that dishes are rinsed with steaming hot water (partly to make it easier for drying) hence rendering the disinfection incomparably more efficient compared to manual disinfecting. Nevertheless, most sales of these machines to private homes were not realized even after the arguments for the advantages and attempts to reduce the cost for acquisition. There appeared to be a more favorable response, Cochrane held, in stressing the availability of such a dishwasher for unobtrusive storage of dirty dishes waiting to be washed later (Fenster, 1999).

Hand washing dishes tends to be quite a resource-intensive and generally less effective form of cleaning and sanitization than modern dishwashing. But that is not the reality in most parts of the world where consumers cannot afford a dishwasher or do not really see its benefits, so most dishes in the world go down the sink. Electric dishwasher prevalence is less than 5% in Southeast Asia and Latin America, but above 10% in Africa, the Middle East, and Eastern Europe. Australia, New Zealand, and Japan are distinct from other countries where over 80% of families have other domestic appliances such as refrigerators, washing machines, and microwave ovens, but the penetration of electric dishwashers is around 40% (Schencking and Stamminger, 2022).

For real-world applications, the 3D printed product should be able to withstand a variety of mechanical and external pressures during use. It is necessary to evaluate the amount of strength for different applications under varied loading situations, and for sure, the physical qualities of 3D printed parts should be the same as of those manufactured by traditional methods, such as injection molding (Ryan et al., 2018). The mechanical properties of 3D printed polymers were tested in terms of tension, compression, bending, cyclic/fatigue loading, impact loading, and creep parameters. The International Organization for Standardization (ISO) and the American Society for Testing Materials (ASTM) establish standard tests for examiners of mechanical properties of additively manufactured objects. Additive manufacturing technologies and standardized mechanical test procedures must meet the requirements of both consumers and industries seeking reliable and consistent material performance (Monzón et al., 2015).

To ensure that the cleaning process is effective, food contact area must be microbiologically evaluated. Remaining food residues on a surface that comes into contact with food indicate that the surface has not been thoroughly cleaned, and the residual of food particles provide nutrients for the development of microorganisms that could become potentially harmful (Singh et al., 2002). It can take up to two days for microbiological techniques, such as aerobic plate counting, to provide information on the microbial state. The ATP bioluminescence (ATP-B) assay, a widely used method for determining microbial contamination and food residues in the food industry, has evaluated the efficacy of sampling techniques and rapid analysers for assessing the cleanliness of the surfaces of food contact materials.

There is a controversy between ATP-B and Total Plate Count (TPC) for aspects of sample tested. ATP-B proves the total cleanliness, while TPC determines the quantity of micro-organisms in a sample being tested (Masuku et al., 2012). According to Lee et al. (Lee et al., 2007), a study conducted on "The impact of manual dishwashing conditions on the survival of bacteria on eating utensils" reported that several parameters can influence the survival of bacteria on food utensils like the type of organic matter substrate, the surface morphology of the utensil, efficacy of the sanitizing agent, and the washing-water temperature. Their results showed that most treatments could achieve 5-log reduction in bacterial burden; however, certain food items like milk fractions had the potential to be tenaciously adhered to the utensil and pose a possible health hazard. The previous research of the authors has shown that cleaning dishes using an electrically-run dishwasher on a program of 65 °C is highly effective at removing bacteria. This was proven for both naturally occurring bacteria and artificially injected bacteria placed on the dishes under inspection. The electric dishwasher cut bacterial contamination to a level below what researchers even discovered on clean dishes stored in a cabinet (Schencking and Stamminger, 2022). This study aimed to focus on how the 10-day operation in dishwashing machine influence the growth of bacterial colonies, the mechanical properties (Tensile, Layer adhesion, Bending and Impact), and thermal property (Temperature test for further heat application) of the 3D printed food contact material, after Polymaker PETG and NonOlien filaments-based cups were printed via FDM printer, then exposed to contamination and washing process for further investigations.

2. MATERIAL AND METHODS

The Stereolithography (STL) files were generated from the Autodesk Fusion 360 software used to design the test specimens. These files were then imported into slicer software (Bambu Studio) to generate the necessary G-code for printing. The specimens were made with Bambu Lab's X1 Carbon FDM 3D printer (China). The FDM 3D printer process parameters and characteristics have been summarized in Table 1 (Kam et al., 2023; Gao et al., 2022).

Printing materials at 0.2 mm layer height takes significantly less time. Lower layer heights mechanically put more strain on the printer part (stepper motors, belts, Z-axis screw). Nozzle size of the printer being used was 0. 4 mm, therefore, the layer height should be 25%–75% of the used nozzle size, that is why 0.2 mm resolution was chosen for this study.

Different food safe 3D printing filaments have their own properties, and it is needed by researchers for specific test purposes. Printing materials for this study were selected based on food safe 3D printing certification (EU 10/2011 (Europe), and Compatibility with FDM Potential for smooth surface finish and temperature resistance/chemical durability for actual purposes. Polymaker PETG (PB01011, Polymaker LLC., China) and NonOilen (Filamentum, Czech Republic) filaments were printed via FDM printer for this study. Polymaker PETG has unique advantages due to its excellent thermal stability, strength, and flexibility, making it superior to many other filaments. It is also user-friendly—consistent, easy to print, and mechanically reliable—and offers the additional benefit of being food-safe (Kumaresan et al., 2023). Polymaker PETG has less warping and better layer adhesion because of easily printable

Table 1. FDM 3D printer process and features (Own source)

Process parameter and/or features	Estimated values
Build orientation (°)	0 (Bending and Tensile), 45 (Impact), 90 (Layer adhesion)
Raster angle (°)	0 (Bending and Tensile), 45 (Bending and Impact)
Layer thickness (mm)	0.2 mm
Infill pattern (%)	100%
Print speed (mm˙s)	50–100
Extrusion temperature (⁰C)	230 (Polymaker PETG), 190 (NonOlien)
Bed temperature (⁰C)	60 (Polymaker PETG), 50 (NonOlien)
Nozzle diameter (mm)	0.4
Filaments diameter (mm)	1.75

materials. It has better mechanical properties in terms of impact resistance, strengths and flexibility. Besides, it has better chemical resistance, as well as clarity and finish surface properties. Theoretically, Polymaker PETG relevant to food contact but not without risks. It is not officially approved for use in the food industry. NonOilen is a commercial bio-filament, an alternative to ABS. The biodegradable filament contains over 35% polylactic acid (PLA), over 55% polyhydroxy butyrate (PHB), and less than 10% natural plasticizer (aliphatic ester). PHB content improves toughness, temperature resistance, and, most importantly, biodegradability. It is compatible with the concepts of the circular economy. It can be used again many times, therefore, there is no more waste, and once the lifetime ends, it can be recycled (Bisin et al., 2023).

2.1. Microbial investigation

Tryptone glucose extract (TGE) agar was prepared with 1,000 mL distilled water, 5 g peptone, 2.5 g yeast extract, 1 g glucose and 15 g agar. Furthermore, diluent was prepared with 1 g peptone and 8.5 g sodium chloride in 1,000 mL distilled water.

A simulated application experiment was conducted on three-dimensional printed cups made of Polymaker FETG and NonOilen materials. The experiment involved storing UHT-treated commercial milk (ultra-high temperature pasteurization, at least 140 °C) for ten days, with three cups each of Polymaker FETG and NonOilen material, totally twelve cups for swab test exposed to the milk matrix for ¼ hours every 48 h. After 24 h, the cups underwent a particular cleaning procedure. Different cleaning procedures were investigated, including standard cleaning using Bosch dishwasher (SMS6HAI01A, Germany) at 70 °C for 90 min and hand wash with 40 °C tap water, detergent and sponge for 5 min. Cleaning methods were validated by microbiological swab testing. Swabs were cultured on agar plates to grow and quantify bacteria (CFU/cm^2). After both cleaning procedures, the cups were ready for swab test. After the swab results from each of the three cups were obtained, the final result for the test was determined by calculating the average of the values from all three cups from each material. Swab test procedures are summarized in Fig. 1.

Microbial contamination was investigated by swabbing the inside surface of the cups and suspending the obtained microbial cells in sterile saline. To conduct the plate count assay, a 10-fold diluted solution was mixed with melted and tempered PCA medium (plate count agar,

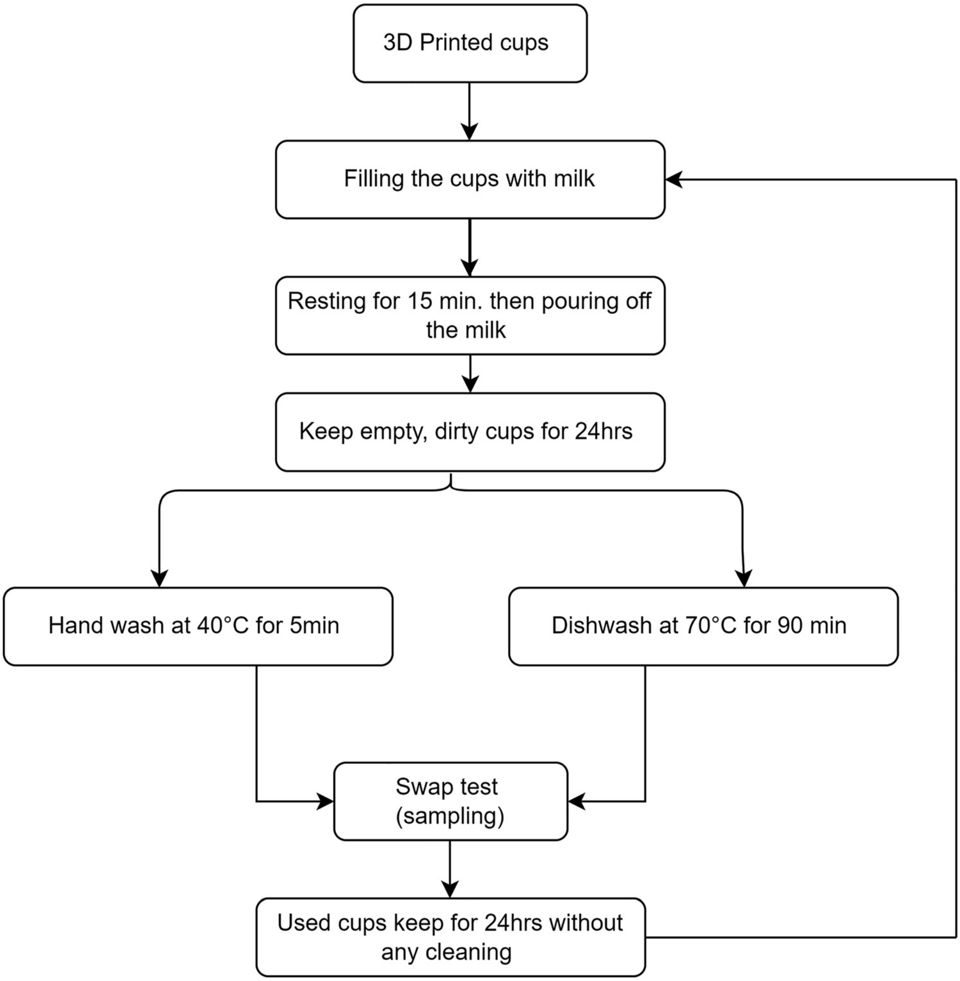

Fig. 1. Flow chart of swab test (Own source)

Himedia Laboratories, India, 50 ± 1 °C). The colonies that developed were counted after a 48-h incubation period at 30 °C. The cell count was calculated as Log CFU/28 cm^2, accounting for sample dilution and the interior surface area of the tested 3D printed cups.

2.2. Mechanical test

After manufacturing the 3D printed specimens based on selected parameters as shown in Table 1 according to ASTMD and/or ISO, and having been subjected to a washing process, then the following mechanical properties of control and washed specimens were investigated. Three specimens were examined to determine their mechanical properties. Each specimen was subjected to the same tests procedure, and the individual results were registered. To obtain a final result, the average of the three test records was calculated.

2.2.1. Tensile test. The tensile test specimen was specifically designed to be compatible with equipment having a maximum load capacity of 200 kg (1962 N). To achieve this, the specimen featured a minimum cross-sectional area of 4 × 4 mm. The top and bottom sections of the part were designed with a 60° alignment angle, allowing them to fit securely into the testing holder. This configuration ensured that the specimen would reliably break at its thinnest point. In the tensile test specimen vertical orientation was the most unfavourable for mechanical strength. Inter-layer bonding (Z-axis) is much weaker than the strength within a single layer (XY-plane), since Layers are fused thermally. A part loaded vertically is likely to delaminate rather than stretch and deform plastically.

The breaking load was measured using a KERN (HCB 200K100) hanging scale, which has the capability to record and display the peak force during testing. Due to the limitations of the apparatus, it was not possible to test objects conforming to the ISO 527-2 standard for plastic polymers, as such specimens would exceed the load capacity of the equipment (Laureto and Pearce, 2018).

To compute the tensile strength at break, we divided the observed breaking force by the minimal cross-sectional area (4 × 4 mm) (Galeta et al., 2016). The tensile stress response at break can be determined using the following formula, derived from the data obtained during testing:

$$\sigma = \frac{F}{A} \tag{1}$$

$$F = m \cdot g \tag{2}$$

where:

σ = stress (in Pascals, Pa),
F = force applied (in Newtons, N),
m = weight (in kg),
g = gravitational acceleration ($9.81\ m\ s^{-2}$),
A = cross-sectional area of the specimen (in square meters, m^2).

The test objects for the tensile test are shown in Fig. 2. The cross-section area refers to the middle part of the specimen, the sides are for proper fastening of the tested part.

2.2.2. Bending test. The bending test was conducted following the ISO 178 guidelines, using a 64 mm span between supports. A three-point bending setup was employed, specifically for specimens that fail below 5% strain. As per the ISO 178 protocol, the total length of the specimen is 16 times its thickness. The specimen should be positioned on the fixture with a 10% offset from either end (Raj and Michailovich, 2021). For this three-point bending test, 10 mm width (b), 4 mm thickness (h) and 64 mm length specimen (Fig. 3.) was examined and its bending modulus of elasticity calculated from (Eq. (3)).

$$E_f = \frac{mL^3}{4bh^3} \tag{3}$$

where:

E_f = flexural modulus of elasticity (Pa),
m = the slope of the initial straight-line portion of the load deflection curve ($N\ mm^{-1}$),

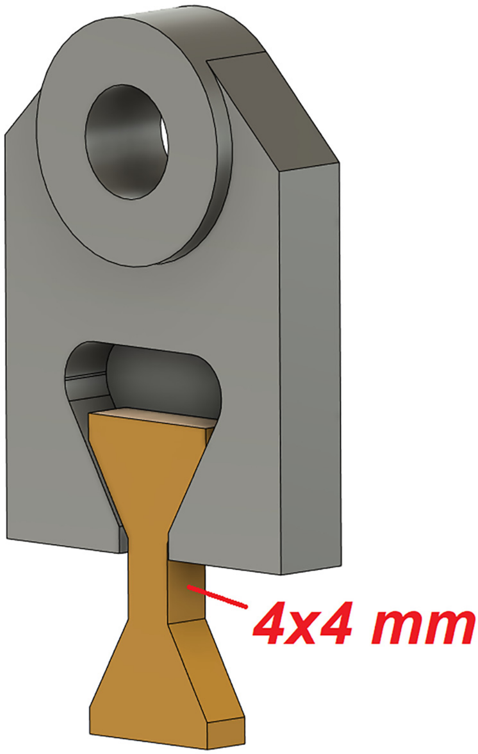

Fig. 2. Tensile test specimen (Own creation)

Fig. 3. Bending test set up (Own creation)

L = the length of the tested specimen (mm),
b = the width of the specimen (mm),
h = the thickness of the tested specimen (mm).

2.2.3. Impact test. The experimental testing of 3D printed specimens was conducted using the IZOD impact test, following the ISO 180 standard. This test evaluates the impact resistance of materials by measuring the energy absorbed during fracture. In Fig. 4, the setup involved an IZOD impact tester, which operates with a pendulum of predetermined weight released from a specific height. The notched test specimen was securely mounted in the testing fixture, ensuring precise alignment for consistent results. When the pendulum was released, it struck the specimen at its notch, inducing breakage. The energy absorbed by the specimen during this process was calculated using (Eq. (4)), providing insights into the material's impact performance and resilience.

$$E = mg(h_{zero} - h_{break}) \tag{4}$$

where:

E = energy absorbed (Joules),
m = mass of pendulum (kg),
g = gravitational acceleration (9.81 m s^{-2}),
h_{zero} = L-L × cos(α_{zero}) (height of zero position or swing position without test specimen, mm),
h_{break} = L-L × cos(α_{break}) (swing position after the break, mm),
L = length of pendulum arm (mm).

2.2.4. Layer adhesion test. From Fig. 5, the specimen geometry is identical to that used in the tensile test, with the only difference being the printing orientation. In this case, the specimen is 3D printed in a vertical position, where interlayer adhesion plays a critical role in the test. The purpose of this mechanical test was to measure the strengths of the bonds between layers and test layer adhesion, in contrast, specimens printed in longitudinal and cross-sectional orientations primarily test intralayer strength, not interlayer adhesion. That is why the vertical orientation is appropriate for testing layer adhesion.

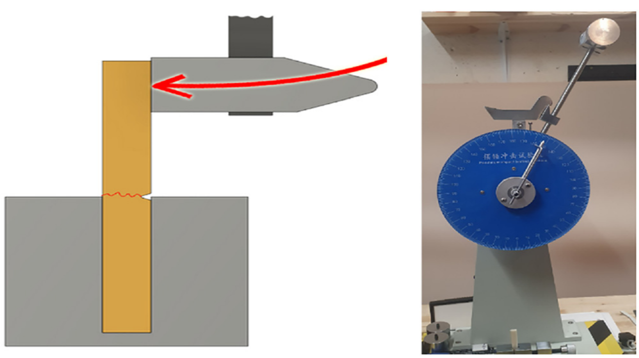

Fig. 4. The Izod impact test (left) and the instrument which was applied in the experiments (Own creation)

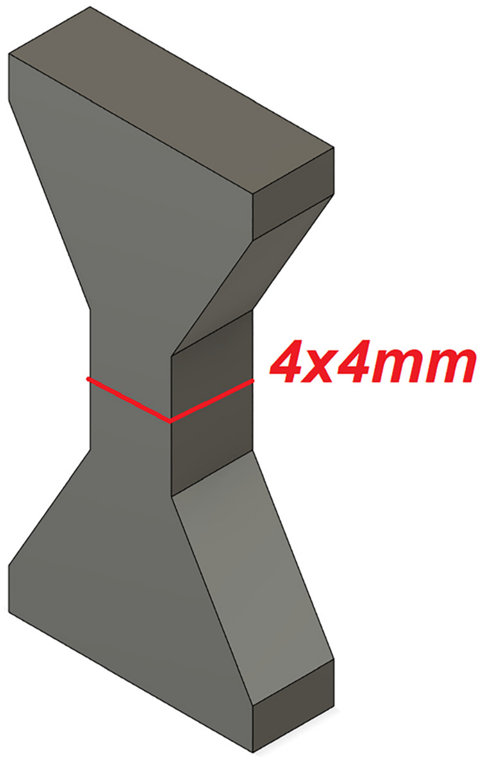

Fig. 5. Layer adhesion test specimen (Own creation)

The applied force during testing is directed along the Z-axis, perpendicular to the printed layers. The same holder and hanging scale are used for the measurement, and only the break load is recorded without measuring the prolongation (García-vilana et al., 2023).

2.3. Heat deflection temperature test

The 3D printed test specimen was evaluated for its response to temperature variations over time. Testing was conducted in a controlled environment using an oven equipped with a measurable and regulated heat source. The sample was printed in a horizontal orientation to eliminate the influence of layer adhesion on the results. The setup featured a support span of 60 mm, with a 10 g load placed at the center of the specimen (Fig. 6). The area dimensions of the examined object were 4 × 10 mm, resulting in an approximate stress of 55.18 kPa. Although this load differs from the standard defined in ISO 75, the test was designed as a comparative experiment under consistent conditions. The specimen was positioned inside the oven, and an external temperature sensor was connected to monitor the environmental conditions (Kim and Cho, 2020).

As the temperature increased, the sample was observed for signs of deformation or softening. The temperature at which deformation begins was recorded as the heat deflection temperature, providing a measure of the material's thermal performance.

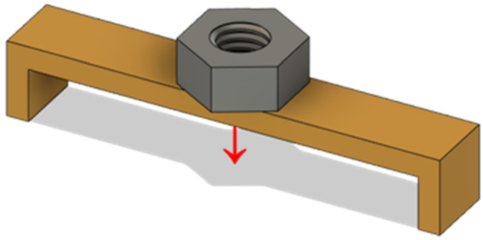

Fig. 6. Temperature test specimen (Own source)

3. RESULTS AND DISCUSSION

3.1. Microbial investigation

The bacterial growth on the cups was measured in terms of Log CFU/cm^2 after the cups were subjected to contamination by milk and to different cleaning methods afterwards. Table 2 presents the results of the effect of washing by hand and dish washing machine treatment on bacterial number (log CFU/28 cm^2) respective to different days under polymer Polymaker PETG and NonOilen filament-based 3D printed cups, which were in direct contact with milk for 15 min prior to the cups undergoing cleaning procedures. As it can be seen in Table 2, apart from the first day, the dishwasher uniformly performs over hand washing in reduction of microbial contamination, as indicated by the lower Log CFU/28 cm^2 values at 1-, 4-, 7- and 10-day time intervals, the differences were particularly pronounced after the longer periods in the case of both materials.

The dishwasher machine has higher temperature, stronger detergents, and systematic mechanical action providing more effective sanitation. These factors ensure that even after more than a week the microbial growth is considerably low, at the suitable level of food safety. On the other hand, manual washing demonstrates good reduction in microbial growth from the beginning, as it gave similar results to the dishwasher, but the results also present that the effectiveness of hand washing decreases over time. The rise in Log CFU/28 cm^2 values over several days proves that microbes are not completely removed and can rapidly reform colonies on the surface

Table 2. Microbial result (Log CFU/28 cm^2) at different time intervals in days (Own creation)

Materials	Testing times (Days)	Hand wash (Log CFU/28 cm^2)	Dishwasher (Log CFU/28 cm^2)
Polymaker PETG	1	1.28	1.30
	4	1.35	1.16
	7	1.43	1.10
	10	1.52	1.06
NonOilen	1	1.53	1.82
	4	1.82	1.62
	7	1.90	1.53
	10	2.17	1.40

of 3D printed cups, especially in areas that are difficult to clean and this fact has to be considered when high level of safety is needed. In contrast to washing by hand, the dishwasher's effectiveness in inhibiting the regrowth of microbes is demonstrated by the fact that the Log CFU/28 cm^2 values remain low even after 10 days, which implies the dishwasher is efficiently cleaning the material and stopping the microbes from regrowing again and therefore it is suggested for permanent use. However, the method of hand washing shows a distinct pattern of microbial regrowth over a longer time, the CFU counts that are observed after 1, 4, 7, and 10 days from both materials (Polymaker PETG and NonOilen) indicate that hand washing does not completely get rid of the microbial contaminants, and as time passes by, the microbes may regrow on the 3D printed material surface. Dishwasher machine is beneficial for long-term food safety as it successfully minimizes microbial contamination and prevents their regrowth on food contact surfaces. This is also significant in 3D printed materials that have complex surfaces which can hardly be hand sanitized. While hand washing may be effective for time saving quick cleaning, it may not be enough for the duration of several days or weeks, depending on the required safety level, to achieve a complete microbial-free surface and therefore additional cleansing might be suggested. This is crucial in potential risk areas, especially in food contact applications, where contamination must be avoided to eliminate such health risks.

Another important result of this test is that the material of the filament effects significantly the cell counts on the test cups. According to Table 2, the measurement found less cell on the Polymaker PETG compared to the NonOilen samples by approximately 20–30 %. This result could be because of the tendency of this polymer mixture to get moisture and presumably the surface properties of the two polymers are different. The phenomena observed in the difference between the polymers in detected cell count was not the part of the present investigation but its closer observation could be part of a future experimental plan in the topic of food safe 3D printing.

3.2. Mechanical test

The following discussion provides mechanical property testing results with respect to the 3D printed specimens of Polymaker PETG and NonOilen filaments before and after the wash. These specimens were processed to observe their possible differentiation due to the effect of washing on tensile strength, layer adhesion, bending, and impact resistance. There were controlled samples kept unwashed for comparisons with the washed specimens. All the data were represented in bar graphs to exhibit the difference in material performances before washing and after washing.

3.2.1. Tensile test. In Fig. 7, the bar graph shows the results of the mechanical test for tensile strength of the Polymaker PETG and NonOilen materials performed before and after washing. The performance of the materials was measured by the the equipment testing the materials' tensile strength (MPa). The data in Fig. 7 clearly show that the Polymaker PETG slightly declines in tensile strength after washing, considering that it decreases from 44 MPa (unwashed) to 42 MPa (washed) which data refers to 448.7 kg cm^{-2} and 428.3 kg cm^{-2} respectively, but this change is not significant from 5% of error viewpoint. Based on these results, the Polymaker PETG 3D printed object is suggested from the aspect of high tensile strength from among the investigated two materials, but the measured 44 MPa is still an order-of-magnitude less than the steel's tensile strength.

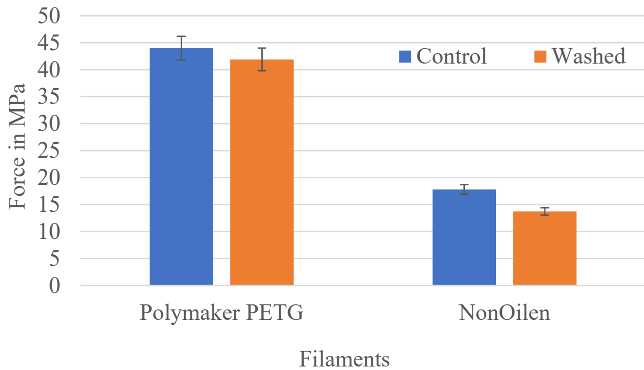

Fig. 7. Tensile strength of Polymaker FETG and NonOilen (Own creation)

In the case of NonOilen, noticeably the measured force was 23% less compared to the Polymaker PETG (4.7%) sample and NonOilen also showed a higher reduction in tensile strength from 17.81 MPa down to 13.72 MPa (181.6 and 139.9 kg cm^{-2}) after washing. This could be due to the tendency of these polymers to absorb moisture and weaken the polymeric chains, as such tensile strength leads to an inability to resist tensile stress. The results also show that the NonOilen filament is suggested to be uses when low impact forces, less than 17 MPa for fresh prints and 13 MPa for prints, undergo regular washing.

3.2.2. Bending test. The results represented in Fig. 8 introduce the difference in bending strength of Polymaker PETG and NonOilen filaments before and after usage and washing. The response of the materials to the applied force was measured by the instrument in bending force (GPa). The washed Polymaker PETG specimen shows an unsignificant difference compared to the unwashed print. The bending strength of 1.84 GPa was measured for the used and washed sample while in control Polymaker PETG a bending strength of 1.76 GPa has been

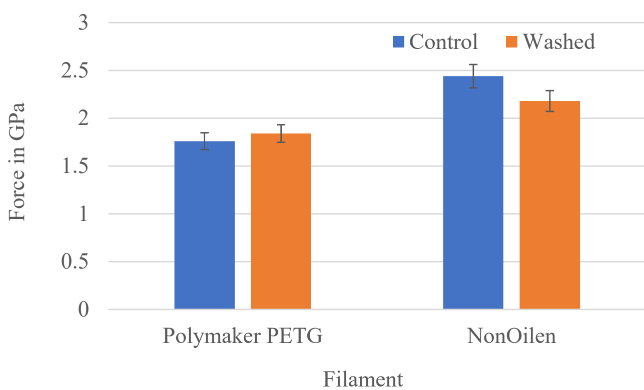

Fig. 8. Bending result of polymaker PETG and NonOilen (Own creation)

found. The NonOilen specimens had definitely higher results in terms of bending stress considering the same Polymaker PETG results.

The washed NonOilen specimen is, however, less than the stress for the control, which was found 2.18 GPa for washed and 2.44 GPa for control sample of NonOilen. This means that based on our experiments the maximum bending strength of the NonOilen decreases slightly but significantly after washing, which implies that the washing process has weakened its tensile strength and stiffness, making it less able to resist bending. It is an interesting fact that the 2 polymers are close in bending test, however, the NonOilen is more resistant but only approximately with 1 GPa, while from the tensile viewpoint the result was opposite, the Polymaker PETG could bear higher force, and the difference between the two tested filaments was higher, the Polymaker PETG's tensile strength has been found 3 higher than that of the NonOilen. NonOilen is made of polyhydroxyalkanoates (PHA) and Polylactic acid (PLA). Based on typical PHA and PLA behaviour: PHA improves toughness, resists high processing temperature and is completely biodegradable, while PLA is known for brittle behaviour in NonOilen.

3.2.3. Layer adhesion test. The most significant effect of washing was found in the change of the layer adhesion. In Fig. 9, the bar graphs are comparing the washed and controlled layer adhesion test results for Polymaker PETG and NonOilen 3D printed materials. Figure 9 shows the differences in adhesion strength found across the investigation of the two materials under the washing conditions, the adhesion strength was reported in force (MPa).

From the observed result, it is revealed that Polymaker PETG is known for its high interlayer adhesion compared to the NonOilen. In its unwashed state, the control sample is naturally expected to show a relatively high adhesion strength, reflecting the material's inherent bonding which takes place during printing. The washing actually decreased the adhesion strength of Polymaker PETG, hence the washed samples have significantly less adhesion strength as compared to the control, which fell from 18.19 to 13.76 MPa. This could be due to either washing removing some of the bonding agents from the surface or leaving residues on the surface inhibiting adhesion.

Washing more adversely and drastically affected NonOilen as it caused a very significant drop in adhesion strength from 12.54 to 1.9 MPa making the objects almost unusable. Currently,

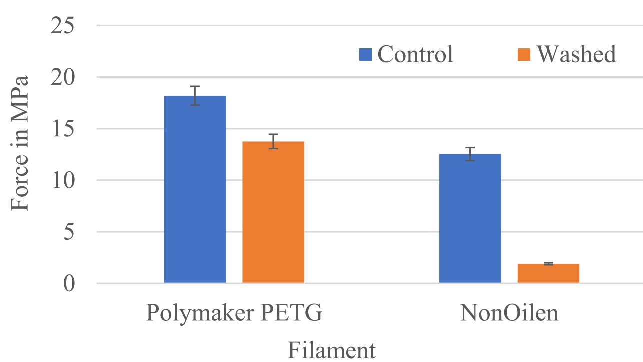

Fig. 9. Layer adhesion of polymaker PETG and NonOilen Specimen (Own creation)

it is unclear whether this specification applies specifically to the NonOilen filament or to other PLA-based materials. The layer adhesion of the washed sample of NonOilen is considerably, an order-of-magnitude less than its control counterpart. From the graph, it was understood that washing has a negative impact on both materials but has an even more noticeable effect on NonOilen (84.8%) compared to Polymaker PETG (24.4%), which is really indicative of the sensitivity of NonOilen's layer adhesion to washing process. The layer adhesion of NonOilen depends on the washing process, for which the temperature of the washing would be necessary, mainly the degree at which the melting point and surface softening (Glass Transition temperature (Tg)) of NonOilen occurs. As NonOilen is a blend of PLA and PHA, the Tg of NonOilen is around 55–60 °C. At this temperature, the surface adhesion of the material is affected since the material starts to soften. Melting temperature (Tm) for PLA based materials usually in the range of 160–180 °C, however, PHA content may alter this temperature slightly, preferably the washing temperature should be below 50–55 °C to avoid premature softening.

This fact suggests that significant and irreversible changes might happen in one or more compounds of the polymer matrix or in a binding (or more bindings) and therefore cleaning by washing is not recommended in applications where high and stable layer adhesion is required. The reason for the high decrease has to be investigated for further understanding in the future.

3.2.4. Impact test. Toughness is a critical measure of all materials, including polymers, and the IZOD impact test is one of the standard methods (ISO 180) for its determination. The technique enables determination of the energy of breakage of the notched specimen after it is swung to strike it with a pendulum hammer. The impact energy per unit of volume, which displays how much energy and damage a material can withstand, is normally presented as an energy in joules. In Fig. 10, the observed energies absorbed of washed and unwashed 3D printed materials like Polymaker PETG and Nylon (referred to here as "NonOilen") expressed in breaking energy (Joule) are introduced.

From Fig. 10, it is obvious that the unwashed Polymaker PETG specimen has an impact energy of 0.19019 J, while the washed Polymaker PETG specimen absorbs 0.14584 J of impact energy, which reveals the negative effect of washing on impact resistance. For the NonOilen, the difference is, however, not much noticeable with the unwashed specimen accepting 0.15673 J and the washed specimen having 0.14584 J.

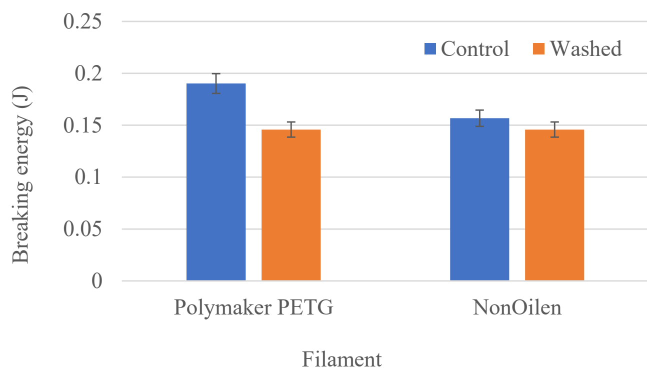

Fig. 10. Absorbed energy by sample of Polymaker PETG and NonOilen (Own creation)

The reduction of impact resistance in Polymaker PETG (23.3%) after washing the material is even more profound. This is due to the fact that washing can cause damage to the printed part either by removing the outermost layers or by adding moisture which may hydrolyze the polymer chain. This is true even more for those materials which are sensitive to changes in postprocessing like Polymaker PETG. As Polymaker PETG is a soft and highly flexible material, it can also incur more damage from washing as some degree of inherent strength of the surface may be lost which would cause cracks and roughness of the surface.

The washing effect does not significantly lower impact resistance for NonOilen (6.95%) after washing process, since it has a stronger chemical structure or can be more tolerant to the incidence of water absorption or surface deterioration. The material maintains its strength even after washing, a fact due to its molecular arrangement as the result of cross-linking.

3.3. Heat deflection temperature test

The Heat Deflection Temperature (HDT) test determines the temperature below which a given material will exhibit deformation under a given load. In essence, it refers to the capacity of a material to withstand temperature without a deformation. A higher HDT is important for applications where the material has to be exposed to high temperatures because it indicates that the material can retain its shape under the influence of heat. Figure 11 presents how the material's sample responds to heat exposure pre- and post-washing. The material's heat deflection temperature was measured (in degree Celsius, °C).

According to the results of this test the washed sample of Polymaker PETG had higher HDT of 74 °C as compared to a lower HDT of 67 °C for a control sample and the significance of this fact is strongly susceptible. This difference implies that washing has a very slight positive effect on the thermal stability of this polymer material. This difference in temperature (7 °C) also leads to marginal improvement in heat resistance of Polymaker PETG after washing or at least no deterioration by washing. In the test of the NonOilen filament, the unwashed sample (139 °C) had slightly higher HDT than what was observed in the case of the washed sample (137 °C), though a very small difference of 2 °C indicates that washing the sample of NonOilen has minimally reduced its thermal stability, possibly due to changes in surface or internal structure of the material during the washing process, but the observed change is not significant.

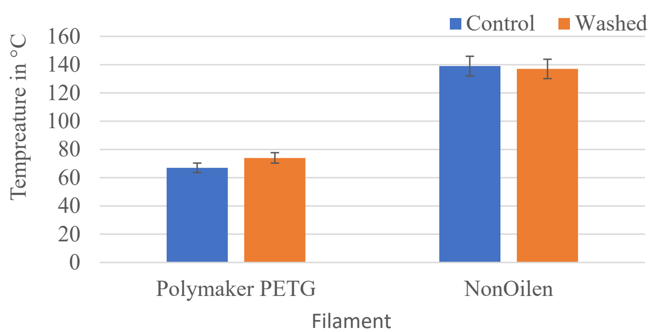

Fig. 11. Heat deflection temperature of Polymaker FETG and NonOilen materials (Own creation)

4. CONCLUSIONS

A simulated contamination and washing of 3D printed food contact-material in perspective of the microorganism's growth and mechanical properties was conducted and the received results were evaluated. In the comparison of the hand wash with the dishwasher washing for reducing microbial growth on 3D printed food contact materials it was found that dishwasher washing proved to be much more effective. The high temperature and detergents employed in dishwashers effectually remove bacteria and food residues, resulting in more and better microbial cleanliness. Hand washing, however, can be effective too, but to quite a lesser degree compared to the above-described method since it involves a manual cleaning process with the use of sponge and lower temperatures, which often leaves more microbes behind. Therefore, it is dishwasher washing which is preferred for obtaining an impressive quality in terms of microbial safety and hygiene for 3D printed food contact materials. Analysis of washed and unwashed 3D printed materials composed from Polymaker PETG and NonOilen demonstrated that dishwashing had negligible positive and negative effects on most mechanical properties like tensile strength, layer adhesion, bending and impact resistance, and also even on heat deflection temperature of the examined materials. Washing also showed almost no significant change for Polymaker PETG, so mechanical properties generally stayed stable or slightly improved. However, the specimens of both materials indicated some loss in impact resistance and heat distortion temperature post-washing, particularly when subjected to very high temperatures in a dishwasher in the case of NonOilen while Polymaker PETG's HDT improved after washing. The research revealed an important connection between dishwashing and the obvious decrease of layer adhesion results of the NonOilen polymer and this phenomenon should be investigated further in future. Overall, it can be concluded that washing increases advantages in the aspect of microbial safety but causes only minimal degradation in mechanical properties of the investigated materials. Repeated washing processes, however, can accumulate into rapid and significant degradation, particularly if the washing involves high temperatures or harsh detergents. When using filament like NonOilen in a multi-use or food-contact application where washing is prevalent, mechanical degradation should be monitored over cycles, and a safe use-cycle limit might need to be established. Further studies should focus on the effect of water, temperature and treatment time as well as their interaction to the molecules or their binding of the polymeric matrix in order to maintain mechanical integrity and hygiene performance after being subjected to systematic washing cycles.

Conflicts of interest: The perspectives stated in this article are those of the author(s) and may not represent those of the funding organization.

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