Supporting Information

Characterization and Control of Nanoparticle Emission during 3D Printing

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Number of Pages: 12

Number of Figures: 5

Number of Tables: 4

This supporting information document contains the following information:

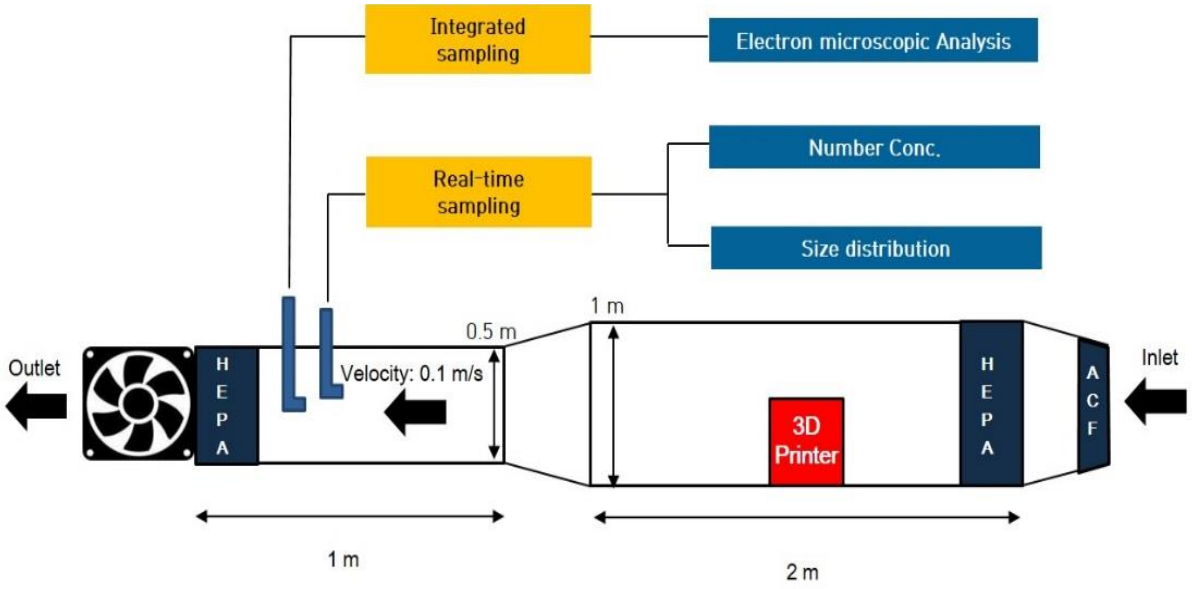


Figure S1. Schematic diagram of the test chamber.

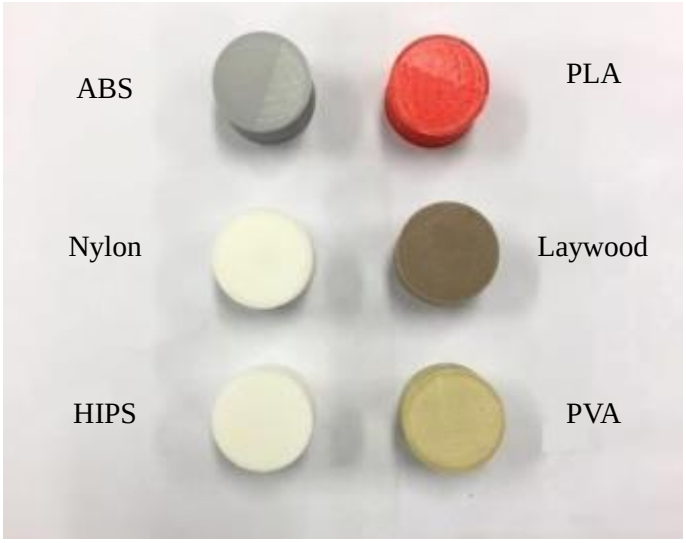


Figure S2. Cylindrical objects fabricated by 3D printing with multiple filament types.

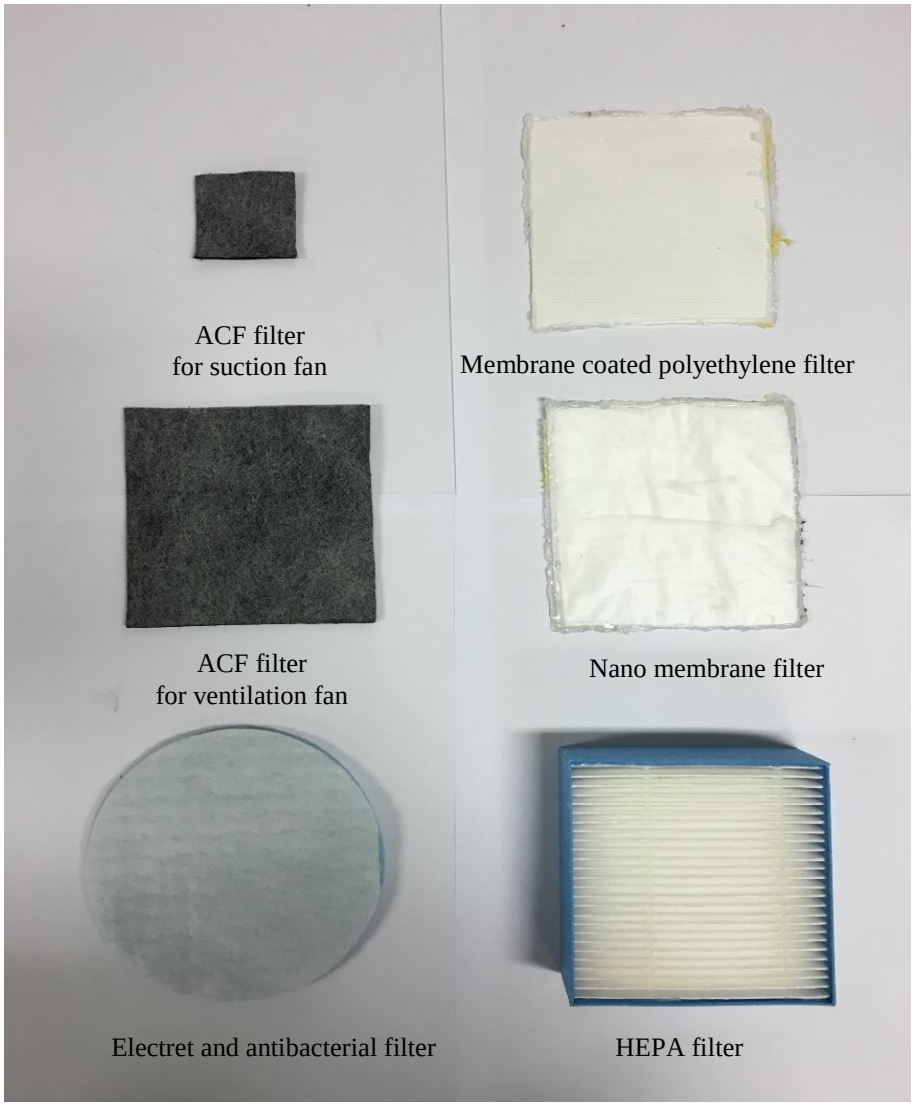
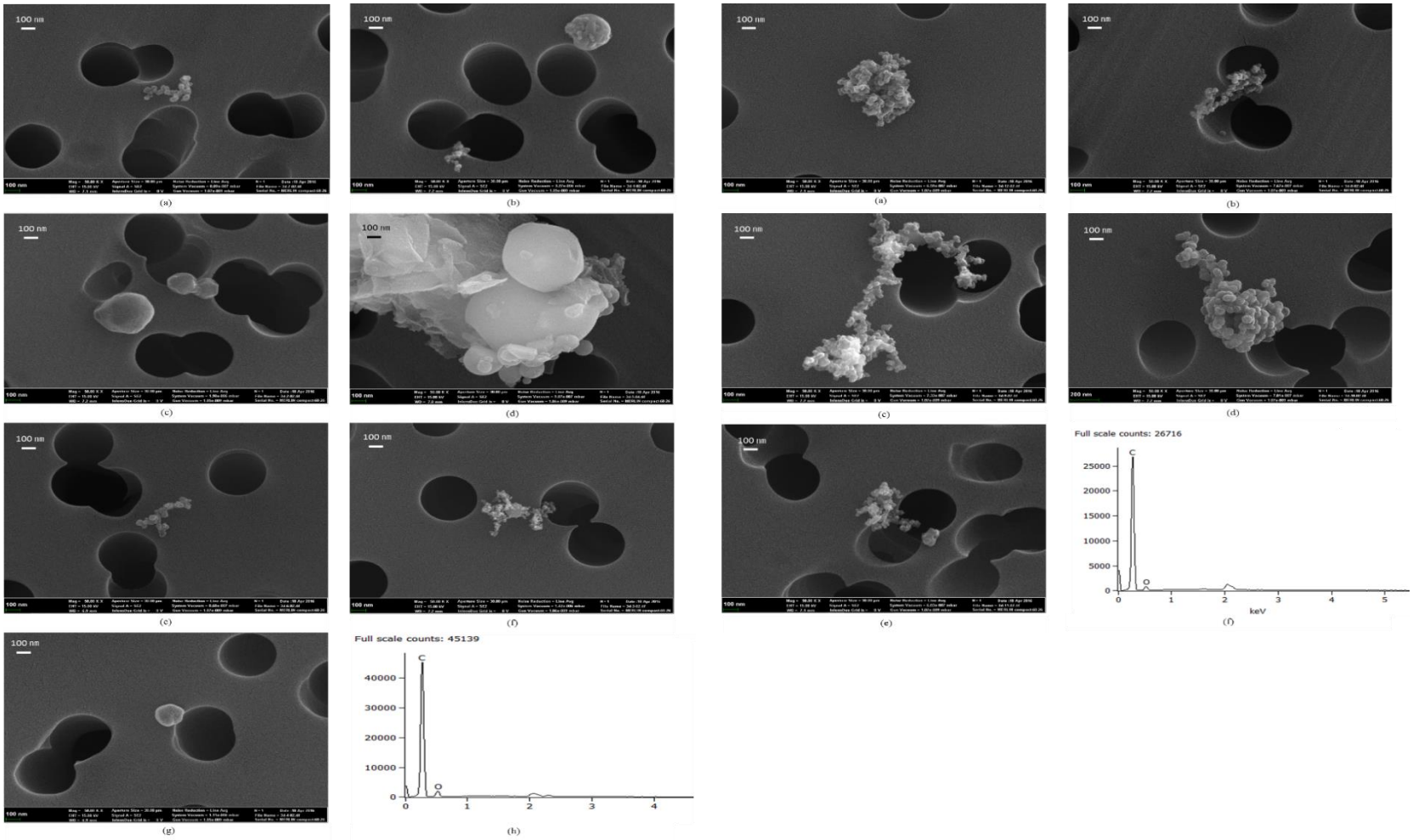
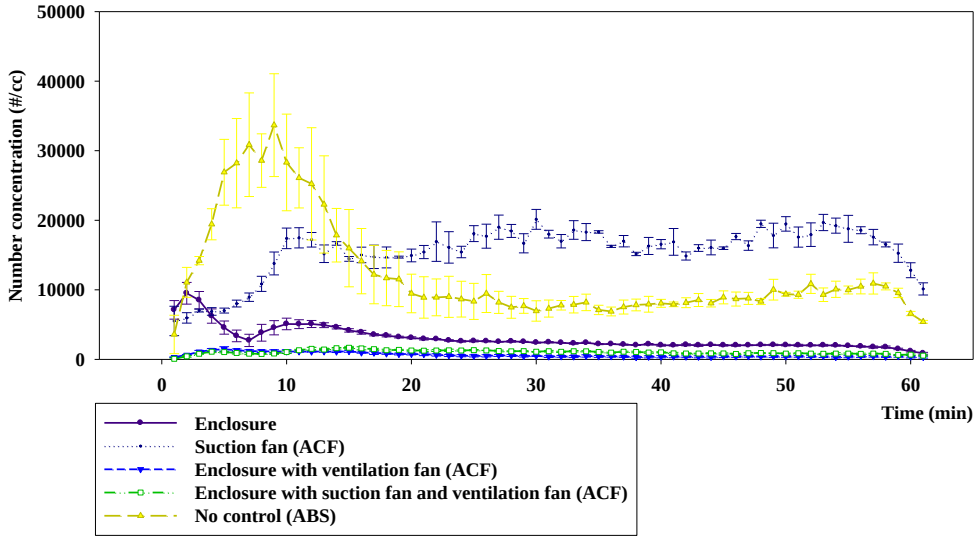


Figure S3. Various filters attached to the back of both the extruder suction fan and the enclosure ventilation fan.

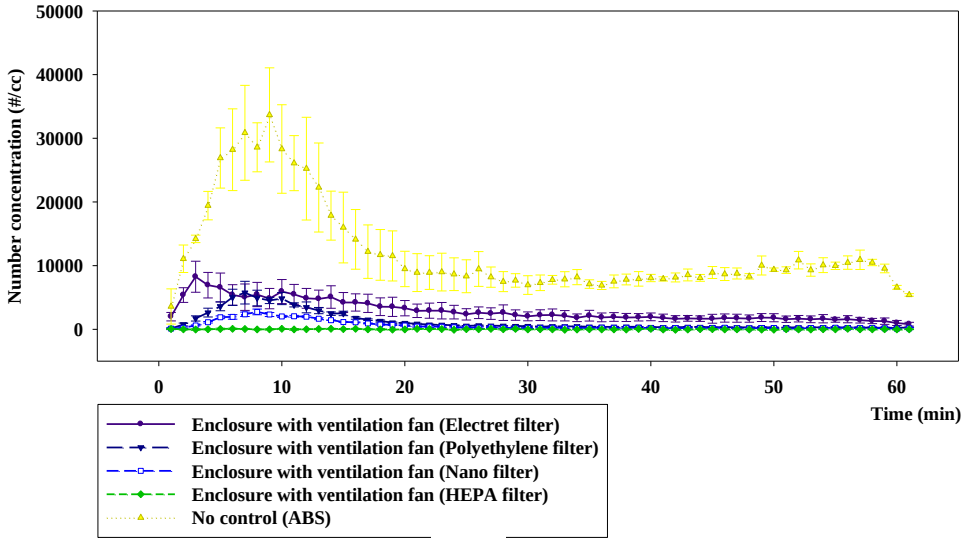


(A) **(B)**

Figure S4. Field emission scanning electron microscope with energy dispersive X-ray spectroscopy (FE-SEM/EDX) images of particles emitted during 3D printing under (A) the manufacturer-recommended and (B) consistent-temperature conditions.



(a)



(b)

Figure S5. Variation in the number concentration of nanoparticles over time during 3D printing for all control methods.

Table S1. Specification of the filters attached to the extruder suction and enclosure ventilation fans

Filter	Manufacturer	Filter media material	Thickness (mm)	Nominal target size	*Removal efficiency (Criteria)	Usage
Activated carbon filter (ACF)	Geoyoungentech, Korea	Activated carbon powder	2.5	-	72% (0.25 μm)*	VOC adsorption, deodorization
Electret and antibacterial filter	Oclaire, Korea	Polyester	5.3	1–10 μm	60–80% (10 μm)	Medium filter of indoor air purifier, antibacterial effect
Membrane coated polyethylene filter	Daejin filter, Korea	Polyethylene	0.5	1–5 μm	99% (5 μm)	Industrial fine-dust filter
Nano membrane filter	Daejin filter, Korea	Polypropylene	1.5	0.2–0.3 μm	96% (0.2 μm)	Industrial fine-dust filter, industrial water purification
High-efficiency particulate arrestance (HEPA) filter[1)]	Oclaire, Korea	Glass fiber	Frame: 35 (Filter: 0.9)	0.3 μm	99.97% (0.3 μm)	High-efficiency particulate air filter

*Notes: Removal efficiency (Criteria) was provided by each manufacturer
[1)] HEPA filter contains twenty-five folded glass fiber filters in a frame

Table S2. Average geometric mean diameters (GMD) measured by SMPS (10–420 nm) during 3D printing under manufacturer-recommended and consistent-temperature conditions.

Conditions	Filament	GMD (nm)	RSD (%)*
Manufacturer recommended	HIPS	31.5	5.3
	Nylon	21.8	4.5
	ABS 1	45.6	18.8
	ABS 2	58.0	21.9
	PLA	57.2	5.8
	PVA	68.0	4.5
	Laywood	59.4	4.8
Operating without filament material	Glue spread	52.1	3.5
	No glue spread	50.4	3.1
Consistent temperature	ABS 1	43.0	17.9
	ABS 2	45.2	18.4
	PLA	27.2	15.8
	PVA	85.2	14.8
	Laywood	30.0	14.6

*RSD: relative standard deviation.

Table S3. Emission rates of various filament materials under the manufacturer-recommended and consistent-temperature conditions during 3D printing.

Conditions	Filament	Nanoparticles (<100 nm)		SMPS (10−420 nm)	
		#/min	#/g	#/min	#/g
Manufacturer recommended	ABS 1	3.00×10^{10}	1.57×10^{11}	3.28×10^{10}	1.71×10^{11}
	ABS 2	1.83×10^{10}	9.54×10^{10}	2.14×10^{10}	1.11×10^{11}
	PLA	3.18×10^{8}	1.32×10^{9}	3.61×10^{8}	1.49×10^{9}
	PVA	5.10×10^{8}	2.28×10^{9}	8.12×10^{8}	3.62×10^{9}
	Laywood	3.53×10^{8}	1.57×10^{9}	4.65×10^{8}	2.07×10^{9}
	HIPS	3.26×10^{11}	3.18×10^{12}	3.37×10^{11}	1.78×10^{12}
	Nylon	3.13×10^{11}	1.56×10^{12}	3.27×10^{11}	1.63×10^{12}
Consistent temperature	ABS 1	1.86×10^{11}	9.61×10^{11}	1.98×10^{11}	1.02×10^{12}
	ABS 2	1.77×10^{11}	9.02×10^{11}	1.89×10^{11}	9.65×10^{11}
	PLA	6.67×10^{10}	2.80×10^{11}	6.82×10^{10}	2.86×10^{11}
	PVA	8.48×10^{10}	3.72×10^{11}	1.42×10^{11}	6.22×10^{11}
	Laywood	6.73×10^{11}	2.93×10^{12}	6.93×10^{11}	3.01×10^{12}

Table S4. Summary of experimental conditions and nanoparticle emission rates from other 3D printing studies.

Authors	Model	Filament material	Extruder temp (℃)	Heating bed temp (℃)	Bed prep	Enclosure	Emission rate (#/min)
Stephens et al. (2013)	-	PLA	200	18	-	-	2.0×10^{10}
	-	ABS	220	118	-	-	1.9×10^{11}
Kim et al. (2015)	Cube, 3D systems	PLA	210-220	-	-	no	4.89×10^{8}
		ABS	250	-	-	no	1.61×10^{10}
	3DISON plus, Rokit	PLA	210-220	-	-	no	4.27×10^{8}
Azimi et al. (2016)	FlashForge Creator	PLA	200	110	Glue	no	$\sim 10^{8}$
		ABS	200	110	Glue	no	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
	Dermel 3D Idea Builder	PLA	230	Room temperature	Alcohol wipe	yes	$\sim 10^{9}$
	XYZprinting da Vinci 1.0	ABS	230	100	Glue	yes	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
	Lulzbot Mini	PLA	190	45	Alcohol wipe	no	$\sim 10^{8}$
		ABS	240	110	Alcohol wipe	no	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
		ABS (CUBE)	240	110	Alcohol wipe	no	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
		HIPS	240	100	Alcohol wipe	no	$\sim 4 \times 10^{9}$
		Nylon	230	65	Glue	no	$\sim 2 \times 10^{8}$
		Laywood	200	65	Alcohol wipe	no	$\sim 8 \times 10^{7}$
		Laybrick	200	65	Alcohol wipe	no	$\sim 6 \times 10^{7}$
		Polycarbonate	270	110	Glue	no	$\sim 4 \times 10^{10}$
		PCTPE	235	65	Glue	no	$\sim 2 \times 10^{10}$
		T-glase	240	60	Alcohol wipe	no	$\sim 5 \times 10^{9}$
	Replicator 2X, MakerBot	ABS	230	110	Glue	no	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
		ABS with enclosure	230	110	Glue	yes	$\sim 2 \times 10^{10} - \sim 9 \times 10^{10}$*
Patrick Steinle (2016)	Cube 2nd generation, 3D systems	PLA	-	-	-	no	2.1×10^{9}
		ABS	-	-	-	no	2.4×10^{8}
Yi et al. (2016)	Replicator 2X, MakerBot	PLA	215	Room temperature	-	no	$1.56 \times 10^{11} - 2.18 \times 10^{11}$**
		ABS	230	110	-	no	$1.04 \times 10^{11} - 2.27 \times 10^{11}$**
Stabile et al (2017).	Prusa i3, Prusa Research s.r.o.	PLA	180 - 240	-	-	no	Negligible – 9.98×10^{10}
		Wood 1	220 - 240	-	-	no	$5.77 \times 10^{10} - 2.64 \times 10^{11}$
		Wood 2	230 - 240	-	-	no	$1.91 \times 10^{12} - 2.78 \times 10^{12}$
		Copper	220 - 240	-	-	no	$1.98 \times 10^{12} - 1.96 \times 10^{12}$
		Bamboo	210 - 240	-	-	no	$1.65 \times 10^{10} - 2.65 \times 10^{12}$

		Flex PLA	240	-	-	no	4.18×10^{10}
		Styrene-free copolymer	220 - 240	-	-	no	$1.68 \times 10^{11} – 1.58 \times 10^{12}$
		Carbon fiber-filled styrene-free copolymer	220 - 240	-	-	no	$2.31 \times 10^{11} – 1.20 \times 10^{12}$
		Nylon	230 - 240	-	-	no	Negligible – 1.55×10^{11}
		NINJA-FLEX	220 - 240	-	-	no	Negligible – 1.39×10^{11}
Floyd et al. (2017)	Aworldnet A600	PLA	210	70	-	no	0.1×10^{8}
		ABS	210	70	-	no	2.7×10^{8}
		PVA	210	70	-	no	1.2×10^{10}
		HIPS	210	70	-	no	0.5×10^{8}
		PCABS	210	70	-	no	6.0×10^{8}
		Nylon	210	70	-	no	1.2×10^{8}
		Bronze-PLA	210	70	-	no	3.9×10^{9}
		PET	210	70	-	no	2.6×10^{8}
Mendes et al. (2017)	miniFactory 3 Education Edition Single Extruder, miniFactory Oy	PLA	200	70	-	no	6.0×10^{8}
		PLA	230	70	-	no	$3.6 \times 10^{9} – 3.1 \times 10^{11}$
		ABS	230	90	-	no	$2.2 \times 10^{10} – 3.7 \times 10^{11}$
		ABS	238	90	-	no	2.3×10^{12}
		ABS	250	90	-	no	1.3×10^{12}
		ABS	230	110	-	no	$2.4 \times 10^{11} – 7.2 \times 10^{11}$
		ABS	238	110	-	no	4.8×10^{11}
		ABS	250	110	-	no	4.8×10^{11}

*In the Azimi et al. study (2016), the emission rates across all ABS printers with or without enclosure were expressed as a range.

**Total particle emission with various color filaments measured by SMPS