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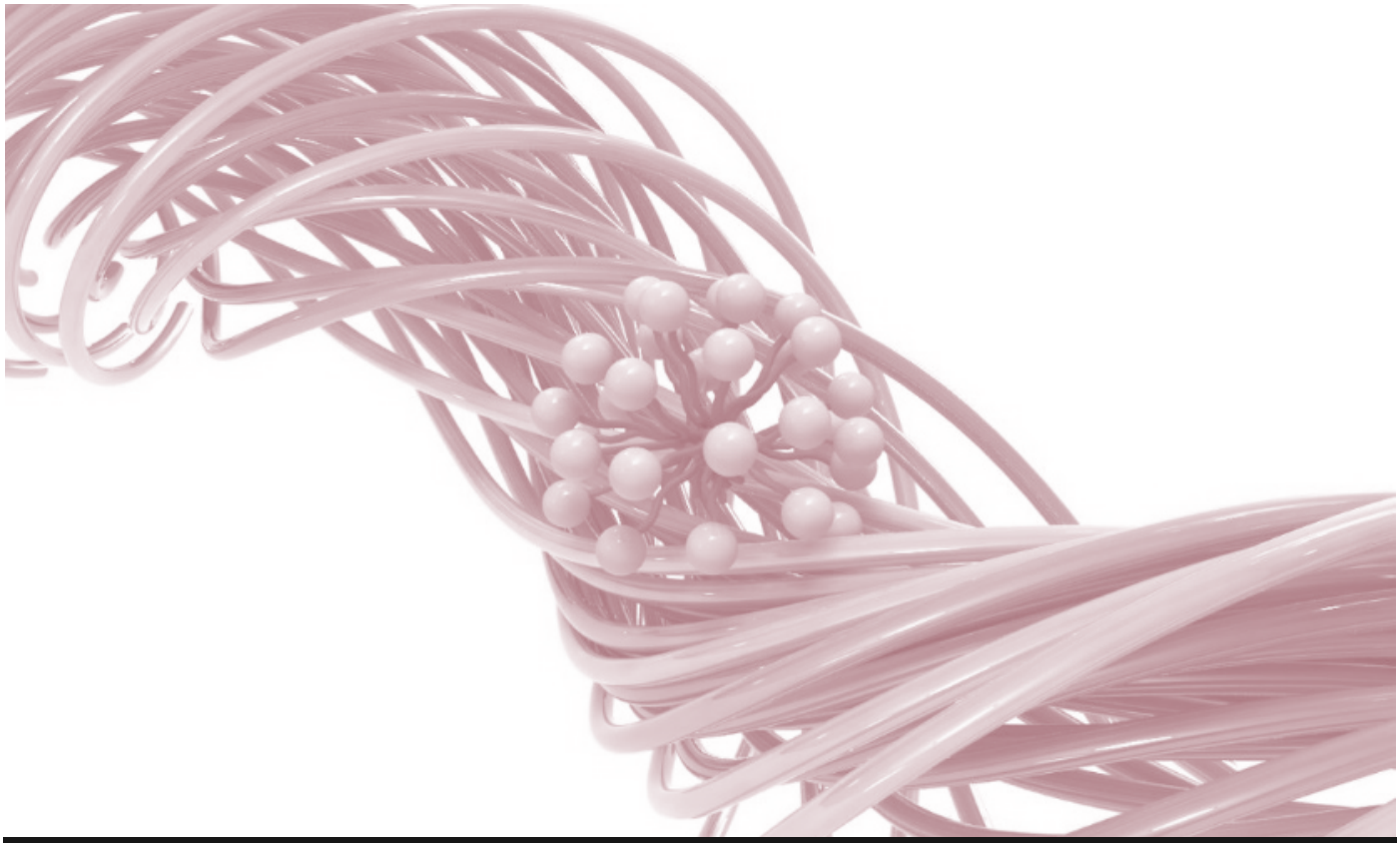

development of ink formulations for On/Off inkjet textile dyeing

by
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summary

The aim of this study was to develop ink formulations based on pigment for coloring and de-coloring of textile to facilitate textile reuse and recycling.

In the first part of the study the critical parameters of the ink development, such as viscosity of the pigment dispersion, pigment size and surface tension for piezoelectric print heads were investigated.

In the second part, two generations of ink were developed. The first-generation ink was designed with the aim of having a limited resistance to water spill. The formulation was developed with a polymeric dispersant and a few additives to reach the target of small pigment particle size and low surface tension and viscosity to prevent clogging the nozzles. The second-generation ink was developed with the aim of being resistant to laundry washing when printed on textile, and to be removed by chemical and mechanical treatments. The ink formulation for the second generation was based on a stimuli-responsive additive which changed molecular structure upon exposure to an external trigger.

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1. introduction

Fast fashion cycles and customization put a high stress on the flexibility of raw materials, contradicting the demand for extended material lifetimes by reuse and recycling. This project aligns with this contradiction and aims at developing an inkjet that can be removed on-demand, thus allowing the possibility of expanding the use of textile by facilitating reuse and recycling. The goal of the inkjet project is to develop an ink for flexible, small scale production of printed/colored textile with the possibility of removing the pattern/color when needed.

Inkjet printing is based on two main technologies, thermal and piezoelectric print heads. In thermal print heads, drops of ink are pushed out of the chamber by the heating of a resistive element. The heated ink causes a nanobubble to form, ejecting the ink through a nozzle. This technology presents a lot of advantages but can be problematic if the ink is thermosensitive. In piezoelectric inkjets, a voltage is applied over the piezo crystal and a pressure pulse is generated in the ink which forces a droplet out through the nozzle. In this study, a piezoelectric print head was used to prevent any damage of sensible additives and eliminate the use of volatile organic compounds.

Ink formulations are generally composed of several components; pigments (not soluble in the continuous phase) or dyes (soluble in the continuous phase), a vehicle composed of water and/or organic solvent (the continuous phase), additives that brings a specific function (dispersant, preservatives, antifoamer) and generally a polymer which enables the binding of the functional molecules. Depending on the nature of the vehicle, different types of ink exist. Solvent-based inks have been the ink of choice for many years due to the printing quality but are today being replaced with water-based ink due to environmental concerns. However, the water-based inks are more challenging to formulate mainly due to the high surface tension of water. In this study, water-based inks using pigments have been developed to facilitate the color removal. Pigments instead of dyes were used to facilitate color removal since dyes in most cases covalently attach to the fiber while pigments adsorb.

Many quality characteristics are of importance in inkjet printing: color strength, print quality, compatibility, adhesion etc., but the primary importance is related to jettability through parameters such as viscosity, surface tension and particle size of the ink formulation.

Two generations of removable inks were here developed. The first generation aimed at removing color during washing, notwithstanding laundry washing, i.e. towards very short-term use. The ink formulations are based on a combination of traditional anionic and non-ionic dispersants. The ink formulation is printed and then washed off, after use. The second generation of ink was based on a pre-treatment of the textile, the color textile withstands laundry washing and is removed by chemical and mechanical treatments. The ink formulation is based on a stimuli-responsive system that switches molecular structure on demand.[1-3]

The stimuli-responsive additive is the key function in the second generation of ink formulation. The cotton is pre-treated by a cationic agent to become positively charged to facilitate the adsorption of the anionic pigment by electrostatic attraction [4-8]. In parallel, the adsorption of the pigment on textile is also driven by van der Waals attraction. During the de-colorization process, the textile is exposed to an acidic environment which facilitates the desorption of the pigment by electrostatic repulsion. The on/off technology is illustrated in figure 1.

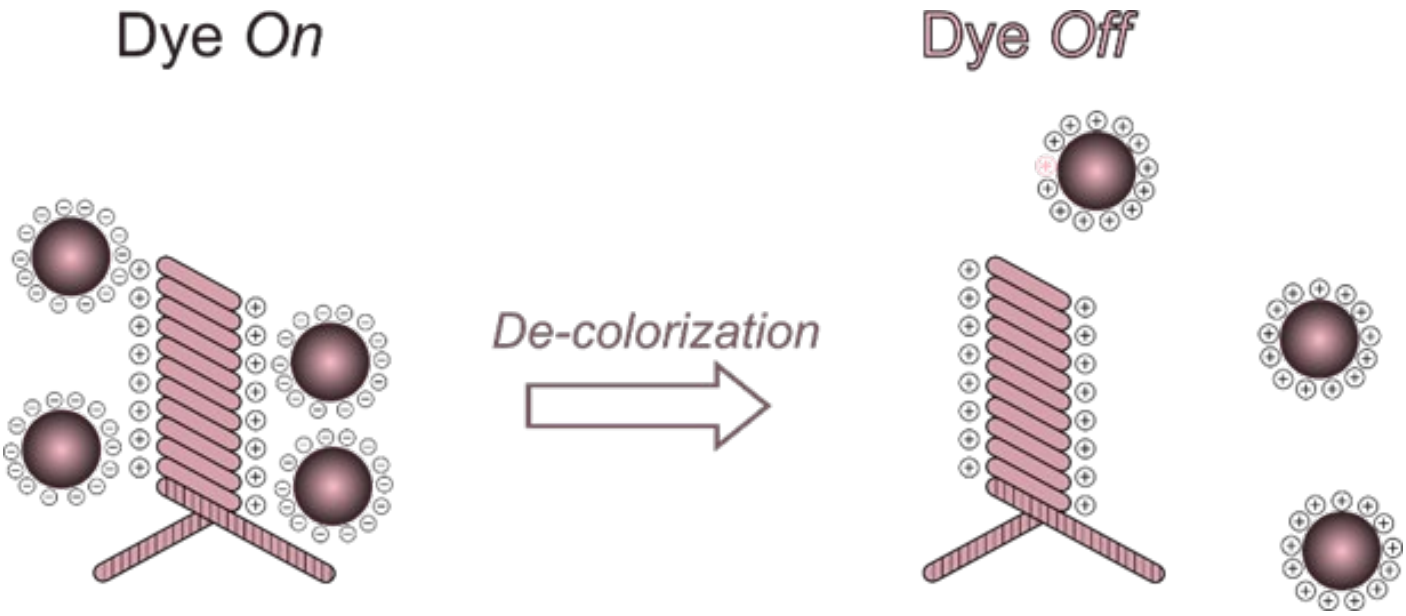


figure 1 Illustration of the second generation on/off concept. The colorization is based on electrostatic and vdW attractions between the cationized cotton and anionic pigment. The de-colorization is based on switching the charge of the pigment from negative to positive to facilitate the de-colorization by electrostatic repulsion.

To early identify the environmental potential and concerns of the second generation On/Off technology, a indicative LCA analysis was also performed. A indicative analysis is associated with certain limitations as data represents lab scale conditions and not large-scale production. However, the early LCA analysis serves as a guideline to identify negative environmental impacts in an early stage. The full LCA report is confidential but part of the results is presented and discussed.

2. results and discussions

2.1. evaluation of the relevant characteristics for a printable ink on the Ricoh Gh2220 print head

In order to be printed correctly, inks must meet several characteristics depending on the type of print head (thermal or piezoelectric) and its requirements. In this study, the print head used was a piezoelectric Ricoh GH2220, mounted on a FabricZoom printer. The main characteristics important for the piezoelectric print head are viscosity, particle size and surface tension. In the below sections (2.1.1 – 2.1.3), the conditions for these three characteristics and how the work to meet them was performed, are presented.

2.1.1. the impact of viscosity on printability

The Ricoh Gh2220 print head is recommended to be used with inks presenting a viscosity of 8+/-0.5 cP (25°C). The viscosity measurements of the two inks provided by the printer manufacturer (cyan and magenta inks) showed viscosity values of 6.95 and 7.15 cP, respectively. Nevertheless, printing with these two inks did not present any issue and the printing quality was satisfactory. Several inks were then formulated and analyzed in order to obtain this range of viscosity.

As a starting point, a basic ink was formulated with the pigment PV23, Polyethylene glycol (PEG) as a wetting agent, alcohol ethoxylate to regulate surface tension, and Sodium dodecyl sulfate (SDS) as a dispersant (Formulation n°1). This ink presented a very low viscosity value of 1.2 cP. Different formulations were then prepared in order to increase the viscosity. Glycerol, PEG and Hydroxyethyl cellulose (HEC) were used to increase the viscosity. The main results are presented in table 1. Formulation n°5 bring together a relatively low amount of glycerol with an acceptable viscosity (7.8 cP). Nonetheless, the printing of this ink was not satisfying, since most of the print head nozzles clogged rapidly after the first printing tests. This was due to the high viscosity of the sample. However, as formulation n°1 was printed with satisfying printing flow, and this was satisfying for the purpose of the study, this value has been chosen as a target value of the viscosity for this study.

table 1 Composition and viscosity of the samples aiming an increase of viscosity using thickeners

formulation	composition	viscosity (cP)
1	Water, PEG200 (0.5%), PV23 (3%), SDS (1%), alcohol ethoxylate (0.5%)	1.2
2	Ref + PEG200 (20%)	2.4
3	Ref + PEG1000 (20%)	3.8
4	Ref + Glycerol (50%)	7.2
5	Ref + Glycerol (30%), PEG200 (10%), HEC (0.2%)	7.8

2.1.2. the effect of particle size

Another important property to consider is the particle size of the pigment. The nozzles of the print head are micrometric (24 µm for the Ricoh GH2220) and to avoid clogging of large particles, a 5 µm filter is positioned right before the print head. Furthermore, smaller particle sizes, preferably less than 1 µm, are required to achieve high printing quality (e.g. color quality) as well as long term colloidal stability of pigment-based ink.

In this study, the pigment dispersions used for the ink formulations were prepared by sonication, and the impact of the sonication technique on the particle size was studied with three samples similar in composition. The sonication intensity effect was assessed, as well as the impact of introducing more complex sonication pulse characteristic (results in table 2). The results demonstrate that a sonication with 20% amplitude (AMP), which corresponds to a power of 100 watt), is preferred over sonication with 60% AMP. A tentative explanation could be that the dispersants are sensible to serious mechanical action, or more exactly from the heat resulting from the sonication. Also, continuous sonication was more efficient in terms of particles size than sonication in several steps. This could be due to the need of an extended mechanical action to form smaller and smaller particles. A continuous sonication with 20 % AMP for two minutes was thus chosen for this study.

table 2 Effect of sonication on particle size of the pigment

	2 minutes at 20% AMP	2 minutes at 60% AMP	Pulse 20 second/ rest 5 second at 20% AMP
Particle size (nm)	150.6	236.8	161.6

It is also of importance to study the optimal amount of dispersant to be used. When the amount of dispersant is very low, one cannot achieve small particle sizes as the amount of dispersant is not enough to cover the large specific area that would develop very small particles. On the other hand, an excessive amount of dispersant can cause an increase of the viscosity. The mobility of the particles is then reduced, and the formation of smaller particles slightly hindered. Results obtained with different amounts of SDS in a formulation are presented in table 3. The effect of the amount of dispersant was minor but visible, with an optimal particle size for 1 w/w% of SDS in the formulation.

table 3 Effect of dispersant amount on particle size of the pigment.

SDS amount (w/w%)	0.3	1.0	2.0
Particle size (nm)	117.6	110.9	116.9

2.1.3. the impact of surface tension

Surface tension is a primary factor determining droplet formation in the printing head and consequently the printability and printing quality. It can be controlled using surfactants or solvents presenting different surface tensions.

Different inks were formulated and analyzed to obtain the recommended range of surface tension for Ricoh GH2220 print head, 25+/-5 mN/m, see results in table 4. The two provided inks, cyan and magenta, had values of 31.5 and 32.6 mN/m, respectively. In formulation A (described in the header of table 4, and similar to formulation 1 in table 1), the surface tension was too high compared to the required value. To decrease the ink's surface tension, two approaches were tested, one adding more SDS, and one adding alcohol ethoxylate (with high interfacial activity) as surfactants. The latter presented the lowest surface tension, in line with the inks provided by the printer manufacturer. For another tried ink formulation, formulation B (described in the header of table 4), the addition of the alcohol ethoxylate yielded the same reduction in surface tension, and the amount was optimized to 0.2%. Printing tests of these formulations showed a good printing flow. Formulation C (described in the header of table 4), which already contained 0.2% of the alcohol ethoxylate, had printing issues and very quickly after the first printing pass, no ink would come out of the nozzles. An additional 0.1 % of the alcohol ethoxylate was hence added to the formulation, resolving the flow issue.

Surface tension is a crucial factor in printability and can be easily regulated with low molecular weight alcohol ethoxylate in various amounts, depending on the starting formulation.

table 4 Effect of surfactants SDS and alcohol ethoxylate on surface tension. Formulation A: 0.5% PEG, 3% PV23, 1% SDS. Formulation B: 0.5% PEG, 1% PV23, 0.5% alkyl amide ethoxylate, 0.45% anionic polyether phosphate. Formulation C: 0.3% non-ionic oxirane monoalkyl ether, 2% PV23, 0.1% anionic polyether phosphate, 0.5% PEG, 0.5% PVA, 0.2% alcohol ethoxylate.

	provided inks		**formulation A**			**formulation B**		**formulation C**	
SAMPLE	Magenta ink	Cyan ink	Reference: No alcohol ethoxylate	+0.5 % SDS	+ 0.5 % alcohol ethoxylate	Reference: No alcohol ethoxylate	+0.2 % alcohol ethxoylate	Reference: 0.2% alcohol ethoxylate	+0.1 alcohol ethoxyla
SURFACE TENSION (MN/M)	32.6	31.5	35.10	34.0	31.5	34.4	30.9	31.46	30.0

2.2. development of the first generation of ink

In this part, the use of PVA (polyvinyl alcohol), a soluble binder presumably able to take away the pigment through dissolution during a washing treatment, was studied. The aim was to develop a printable ink with a certain color resistance to slight water exposure, but removable with simple washing machine detergents and conditions.

Based on the results obtained in the last section, the formulation was adapted to be compatible with the use of the binder. The attention was mainly focused on obtaining the smallest particle size, to ease the printing and obtain satisfying high color strength. As the use of polymers can change the bulk properties and entails larger particles size, the first step was to find a better dispersant than SDS. Indeed, in the last formulations, dispersions containing SDS as a dispersant needed the prior use of polyethylene glycol (Mw 200 g/mol, PEG 200) as a wetting agent. New formulations without this wetting agent were tested with three polymeric dispersants; a non-ionic oxirane monoalkyl ether, and two different anionic polyether phosphates. Formulation using the non-ionic oxirane monoalkyl ether as the dispersant presented the smallest particle size (114 nm) and was therefore selected as the main dispersant. Furthermore, to enhance stability of the pigment dispersion by introduction of negative charge, a combination of the non-ionic oxirane monoalkyl ether with an anionic polyether phosphate dispersant was also studied. The combination of the two dispersants resulted in slightly larger particle size (118 nm) compared to use of only the non-ionic dispersant, however, to enhance stability over time the pigment dispersion based on the combination was chosen for further studies.

The optimal amount of dispersant to be used was also investigated. A smaller particle size was obtained with 0.3% of the non-ionic dispersant in the dispersion, with a value of 114.3 nm compared to 145.9 nm with 1% of the non-ionic dispersant in the dispersion. The effect of an excess of dispersant was more pronounced in this case than with SDS, as the non-ionic dispersant presents a higher molecular weight than SDS, and hence the hydrophobic chains cause a dramatic increase of the viscosity. Smaller particles are then harder to obtain due to reduction of the mobility of the particles.

Then the effect of the addition of PVA as polymeric binder was studied. It was observed that the presence of PVA significantly increased the size of the particles. An additional sonication step after mixing at 20% amplitude for 2 minutes solved however this problem. After sonication the particle size was almost equal to that of the formulations without PVA.

The impact of the use of PVAs of different molecular weight was finally investigated. The molecular weight of PVA was expected to play a role in the ink removal step, as it would affect its dissolution. As expected, the lower molecular weight, the easier was the dissolution of the polymer in water. As for the particles size, presented in table 5, the two lowest molecular weight PVAs resulted in a better dispersion than the PVA of higher molecular weight. This result can be explained by an improved mobility of the polymer chains when they are smaller.

After the particle size was improved, and the surface tension was controlled and adapted with alcohol ethoxylate, the formulations containing the different PVAs were scaled up, printed and tested for color removal.

table 5 Effect of PVA molecular weight on particle size. The formulation used consisted of 1% PV23, 0,3% non-ionic oxirane monoalkyl ether, 0.1% anionic polyether phosphate, 0.5% PEG, 0.5% PVA, 0.2% alcohol ethoxylate.

PVA (87-89% hydrolyzed) molecular weight (g/mol)	13-23k	31-50k	88k
Particle size (nm)	118.7	118.6	150.6

2.2.1. improvement of the color removal

Different formulations were tested to evaluate the effect of the PVA binder; its molecular weight and the de-coloring method on the color intensity loss. The aim was to find the right combination of method and formulation to easily remove the color, while keeping a good resistance to mild water spill. The results presented in table 6. Color removing tests (de-coloring) were performed using washing in washing detergent at 60˚C or using sonication in a 2% SDS, 0.5% anionic polyether phosphate dispersion. The sonification was here used to provide the sample with sound energy to speed the de-coloring reaction by breaking intermolecular interactions.

For all the methods used, color intensity loss is generally more significant when the formulation contains PVA. This demonstrates that the soluble binder helps to wash off the pigment. This is an advantage for the removable aspect of the ink but a disadvantage in the loss of water resistance. However, there is a difference between the PVAs of different molecular weight. Indeed, the formulation containing low molecular weight PVA reaches the best percentage of color intensity loss in a washing machine detergent (57.6% compared to 32.7% for the high molecular weight PVA) and resist better to cold and hot water. Moreover, this formulation showed the highest color intensity after printing.

The low molecular weight PVA (13-21k) seems to be the binder of choice for the target of this study, offering better color intensity, better water resistance, and easy removal by a simple method of de-coloring (figure 2).

table 6 Effect of the binder and de-coloring method on the color removal. The base ink formulation used was based on 1% PV23 pigment, 0.3% non-ionic dispersant, 0.1% anionic polyether phosphate dispersant, 0.5% PEG, and 0.2% alcohol ethoxylate.

		% color intensity loss			
sample	PVA addition	cold water	hot water	sonication	washing detergent (60°C)
1	No PVA	2.2	10.9	16.81	31.6
2	0.5% PVA 88k	16.5	22.0	37.4	32.7
3	0.5% PVA 13-21k	8.7	11.2	8.4	57.6

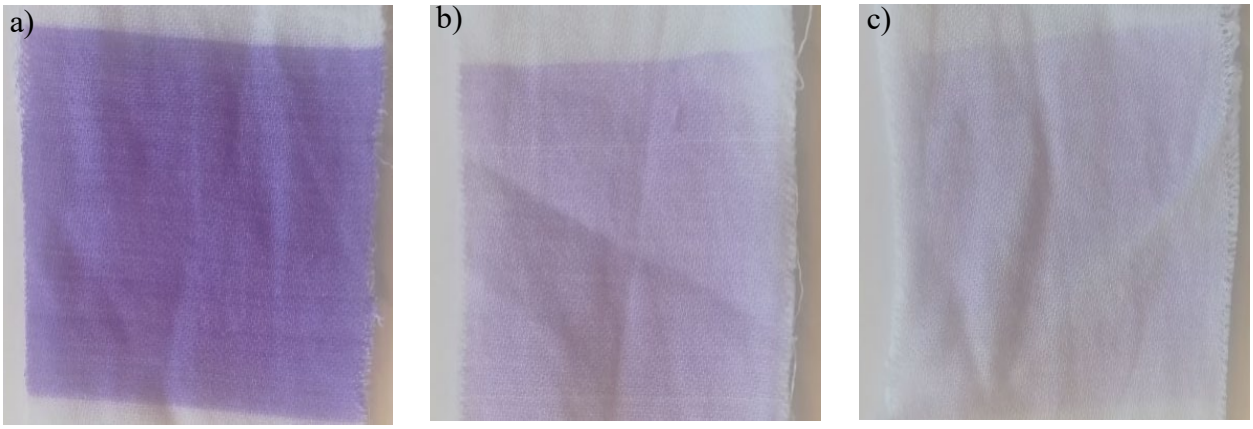


figure 2 Photographs of cotton printed with the formulation containing PVA 13-21k (sample 3 in table 6. a) No de-coloring. b) De-coloring with sonication in a 2% SDS, 0.5% anionic polyether phosphate surfactant. c) De-deyeing with a washing machine detergent.

2.2.2. refinement of the formulation using another pigment

Printing of formulations containing the pigment PV23 were satisfying in terms of flowing through the nozzles. However, the color intensity was very low, and several layers (17) of printing had to be carried out to achieve a sufficiently high color intensity. Furthermore, the amount of pigment present in final inks differ from the amount applied to the sample, because of a centrifugation step removing large aggregates to prevent clogging is causing a substantial loss. With a final dispersion containing more pigment, color intensity would increase and one printing layer would be satisfying, easing the removal of the color, since each layer goes deeper and deeper in the fiber. It was hypothesized that the use of a less hydrophobic pigment could therefore be beneficial.

Therefore, pigment HB 15:3 replaced PV23 in the next formulation (sample 4 in table 7), while all other components and amounts were kept the same as in sample 3 from table 6 (also described in the header of table 7). However, this formulation did not present a more satisfying color intensity after printing compared to the formulation based on PV23. The colored textile showed satisfying results in terms of de-coloring, on the other hand. The subsequent sonication techniques, performed to fixate the ink, showed good results, but again, washing detergents technique appeared to be most efficient, with a color intensity loss of 58.5% which is similar to the same formulation with PV23.

The lack of color intensity is however not a central issue, since this often can be altered by the printing settings. Printings settings relate to the electrical characteristics of the pulse sequence that drives the piezo element of the printhead (voltage, pulse lengths, frequency, etc.). In this study these parameters remained unchanged and not optimized. Typically, this would be a focus of up-scaling.

table 7 Color intensity loss of ink formulation containing pigment HB 15:3. The Ink formulation was based on pigment HB 15:3 (1%), 0.3% non-ionic dispersant, 0.1% anionic polyether phosphate dispersant, 0.5% PEG, 0.2% alcohol ethoxylate and 0.5% PVA (13-23k).

sample	% color intensity loss			
	cold water	hot water	sonication	washing detergent (60°C)
4	23.4	21.4	53.0	58.9

2.3 development of the second generation of ink

In this part, the use of a stimuli responsive additive in the ink formulations was studied. The aim was to develop an ink able to adsorb or desorb to a pre-treated fabric (cationization) and that would be resistant to washing.

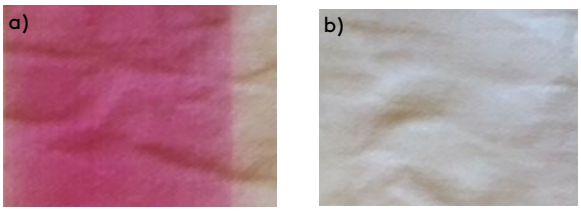
A formulation containing pigment Red 122, wetting agent (PEG 200), anionic polyether phosphate dispersant and the switchable additive was prepared under the right pH conditions. Printing and color removal were performed on cationized cotton and analyzed with colorimeter (table 8). Color removal by sonication showed a color intensity loss of up to 77.7 % (see figure 3). Also, the removal of the color was more significant compared to the first generation, which demonstrates that part of the color removal is stimulated by the switch of charge. The charge of the pigment was negative before coloring (Zeta potential (ζ)= -35 mV (+/- 5 mV)) and after de-coloring positive of charge (Zeta potential (ζ)= +44 mV (+/- 5 mV)), illustrating the concept of switchability.

Washing tests with detergent was performed at 30 and 60˚C and the results are presented in figure 4. The result of the color loss of the sample washed at 30˚C was acceptable, below the just noticeable differences, which means that the color loss could not be observed by the human eye. On the other hand, when washed at 60˚C, the color loss was significant. In summary the second-generation ink formulation based on stimuli-responsive additive showed acceptable technical results under lab-scale conditions.

table 8 Color intensity loss of ink formulation containing pigment Red 122

	% color intensity loss of cationized cotton
Red 133 (4%)	77.7

* Ink formulation based on pigment Red 122 (4%), PEG 200 (10%), amine-based additive (1.2%) and anionic polyether phosphate (1.2%)



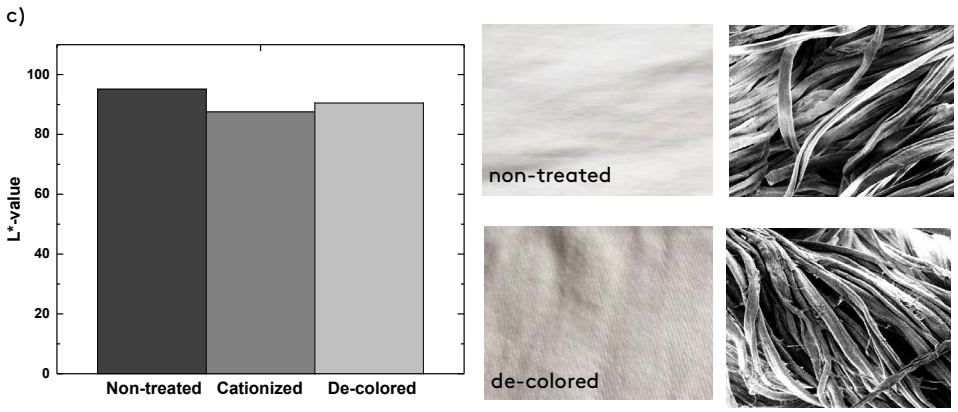


figure 3 a) Ink formulation based on pigment Red 122 printed on cationized cotton b) de-colored with sonication c) L*-values of non-treated, cationized and de-colored cotton, including visual image and SEM of non-treated and de-colored cotton

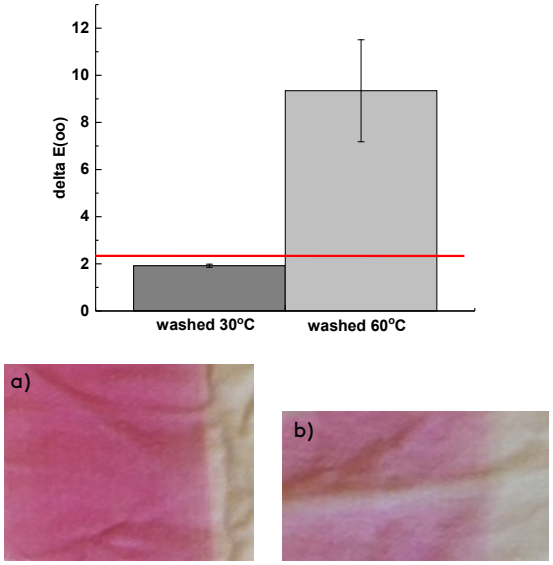


figure 4 Ink formulation based on pigment Red 122 and switchable additive printed on cationized cotton, with delta (Eoo) values of the washed textiles. The red line is the threshold for the just noticeable difference a) washed at 30˚C b) washed at 60˚C

3. environmental foot print

A life cycle assessment study was conducted of the second-generation technology. The purpose of this assessment was to investigate the environmental impact of the decoloring process and the associated coloring process, i.e. the “On-Off coloring”.

Life cycle assessment (LCA) is a technique to assess environmental impacts associated with all the stages of a product's life from cradle to grave, i.e. from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, to disposal or recycling. Environmental impacts include emissions to air, water and soil as well as consumption of resources in the form of both energy and material, in the different stages of the life cycle. The assessment includes different environmental aspects ranging from toxicity and associated effects on humans and the environment to climate change presented as carbon foot print.

3.1. Method

The goal was to identify if, and how high, the environmental savings would be if the user phase of a garment could be prolonged by using the “On-Off coloring” innovation. As a benchmark/reference case, the case of a t-shirt was used, printed with conventional printing paste according to the previous Mistra Future Fashion model (Roos et al., 2015). In both the reference case and the On-Off case, a set scenario was described – a consumer picks up the t-shirt in a store and use it 50 times. During this time, 50 washes in household washing machines are accounted for. For the On-Off case the garment is then de-dyed and used one additional set, i.e. 50 uses and 50 washes.

The assessment included general data for the whole life cycle based on previous studies within the program. In relation to this novel process, specific data was collected and included in the LCA model. For the chemicals used, a chemical risk assessment was performed. The complete report is confidential, and the analysis should more be seen as an early guideline for future development since it is performed on the lab-scale technology and not up-scale production, and therefore certain limitations of the data is associated with the analysis.

3.2. Results

The results in this preliminary LCA study indicate that there are indeed potential savings in terms of environmental impact with the On-Off innovation. The largest improvement is found in the impact category “Acidification” where a reduction of 34% is seen, followed by “Global Warming Potential” which is reduced by 26% of the carbon footprint. However, the reduction in one environmental impact category might be offset by an increase in another category. Here the results show an increase in freshwater ecotoxicity impact with 17% and an increase of human toxicity, non-cancer with 6%. This is related to part of the chemistry used in this study. The chemical risk assessment show that there are two chemicals that are of concern and that may

be regulated for industrial use within the EU in the future. In addition, one substance is classified as biocidal and are under review for process and in can preservative. This latter part is, however, only speculative.

4. conclusion

The aim of this study was to develop ink formulations based on pigment for coloring and de-coloring of textile to facilitate textile reuse and recycling.

In the first part of the study the critical parameters of the ink development, such as viscosity of the pigment the first formulation (nr 1 in table 1) was printed with satisfying printing flow, and since this was satisfying for the purpose of the study, the viscosity was chosen as a target value for this study even though it differed from the recommended viscosity for the Ricoh Gh2220 print head. Furthermore, it was showed that the smallest particle sizes were obtained using a continuous sonication with 20 % AMP for two minutes, as well as an optimal amount of 1 w/w% SDS dispersant used, even though the difference between the concentrations tried was minor. The surface tension is a crucial factor in printability and was shown to be regulated with low molecular weight alcohol ethoxylate in various amounts, depending on the starting formulation.

In the second part, two generations of ink were developed. The first-generation ink was designed with the aim of having a limited resistance to water spill. The addition of PVA (polyvinyl alcohol), a soluble binder presumably able to take away the pigment through dissolution during a washing treatment, was studied. Adding 0.5 w/w% of low molecular weight PVA (13-21k) binder resulted in the best formulation, offering better color intensity, better water resistance, and easy removal by a simple method of de-coloring.

The second-generation ink was developed with the aim of being resistant to laundry washing when printed on textile and to be removed by chemical and mechanical treatments. The ink formulation was based on a stimuli-responsive additive which changed molecular structure upon exposure to an external trigger. The results showed that the second-generation ink formulation based on stimuli-responsive additive gave acceptable technical results under lab-scale conditions when washed at 30˚C, below the just noticeable differences, which means that the color loss could not be observed by the human eye. On the other hand, when washed at 60˚C, the color loss was significant.

All these ink formulations still need to be improved and the technology has only been tested in lab-scale. The preliminary LCA indicates savings on climate impact can be achieved but that the impact category toxicity must be further considered. This positive effect can of course be amplified if the re-use is extended to more than one use, combined with shorter life cycles, which is aligned with the consumers' needs. The LCA indicated reduction in impact of the textile (compared to buying a new t-shirt), especially on the water consumption, but toxicity and ecotoxicity must be assessed in further details. Therefore, the LCA will be used for future developments of the chemicals used in the on/off technology.

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Mistra Future Fashion is a research program that focuses on how to turn today's fashion industry and consumer habits toward sustainable fashion and behavior. Guided by the principles of the circular economy model, the program operates cross disciplinary and involves 60+ partners from the fashion ecosystem. Its unique system perspective combines new methods for design, production, use and recycling with relevant aspects such as new business models, policies, consumer science, life-cycle-assessments, system analysis, chemistry, engineering etc.

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