Working together for a world without waste

Final report – Background study

Thermochromic inks and reducing household food waste

A scoping study to investigate the possible applications of thermochromic inks for household food and drink waste reduction. The report's focus is on 'reversible' thermochromic inks to trigger storage behaviour change at the household level.

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We work with businesses, individuals and communities to help them reap the benefits of reducing waste, developing sustainable products and using resources in an efficient way.

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Front cover photography: Douwe Egberts 'Cafinesse'

Executive summary

The purpose of this study was to describe the current applications of thermochromic inks in order that WRAP, and the food industry, can consider how they might help reduce household food and drink waste. In the process of researching the topic, 20 major companies were interviewed, ranging from food suppliers, thermochromic ink developers, manufacturers and packaging converters.

Thermochromic inks are temperature sensitive materials which change colour with heat. Thermochromic inks come in two forms: liquid crystals[1] and leuco dyes[2], with leuco dyes more commonly used in packaging applications.

To date, thermochromic inks have found most of their applications as 'packaging theatre', for instance alerting consumers that a product is cool enough to drink. In addition, along the food supply chain, liquid crystal inks have been used in thermometers for freezers and fridges to indicate that the temperature is out of the desired range. Time temperature indicators (TTIs) are related technology, already available on the market, used to record the history of time and temperature excursions. At present, TTIs are more commonly applied to multiple-unit, secondary packaging or tertiary packaging.

Approximately 60% of household food waste arises from products 'not used in time', mainly perishable or short shelf-life products, with a value of around £6.7 billion[3]. WRAP wanted to investigate whether thermochromic ink technology could play a role in educating consumers of the need to undertake dynamic in-home storage practices for key foods. For example, keeping apples and tomatoes in the fridge to prolong their life, but returning them to ambient temperatures for the best taste, to maximise eating quality. Research[4] shows that many consumers are still storing their apples at ambient temperatures, despite evidence that they will last longer if stored in the fridge[5].

Reversible thermochromic inks could play a role by alerting consumers that a product is not being stored at the correct temperature. The label could change from indicating "I'll last longer" when cold to "I'm ready to eat" at ambient temperatures. If this type of label is accompanied by marketing, explaining what consumers should look for, it may help lead to behaviour change. Another way they could be used to kick-start behaviour change is through a single reveal message. A great example was found in Douwe Egberts' use of thermochromic inks to encourage customers to store their new 'Cafinesse' product in the fridge, by revealing a competition entry at chilled temperatures[6]. This idea could be adapted to show a fun message, engaging consumers to adopt the new behaviour. For example, a label on an apple pack could say "refrigerate to reveal my secret message" and when cold reveal a message of "apples will stay fresh twice as long if kept in the fridge". The new behaviour would be retained by the consumer noticing that the product did indeed last longer meaning that the trigger need not be applied on an ongoing basis.

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[1] When activated, liquid crystal ink changes through a spectrum of multiple colours.

[2] The common use of the thermochromic leuco dyes in the market is to reveal an image or another colour printed beneath when activated.

[3] http://www.wrap.org.uk/content/new-estimates-household-food-and-drink-waste-uk

[4] WRAP bi-annual consumer survey, selected results available at: http://www.wrap.org.uk/sites/files/wrap/CFWPS.pdf

[5] http://www.wrap.org.uk/content/helping-consumers-reduce-fruit-and-vegetable-waste

[6] A similar example is shown in Figure 17 of the main report; Budweiser beer 'Chill and Win' game cards.

Thermochromic inks based on leuco dyes are very easy to apply with practically no difference to other packaging inks and, for reversible leuco dye inks, the same machinery can be used. They are more expensive than normal inks to buy, but as small quantities are used they have little effect on costs of overall packaging. When printed, the thermochromic inks can last for years exhibiting colour change; however, extensive exposure to UV light will adversely affect the lifespan of the ink. Packaging users need to seek regulatory guidance and undertake specific testing in order to make sure that the thermochromic inks (as any other inks) are compliant with direct food contact use, and this report highlights examples of where these inks are already in use.

There are related technologies, either available or being developed, that could also have significant benefits in helping consumers improve their food storage behaviours. For example, Freshpoint has created 'Time It'[7] while Insignia Technologies[8] has developed a new label. Both are activated when there are changes in the CO_2/O_2 balance within the pack when the pack is opened. Such technologies provide valuable information as to the freshness of many products and when they should be eaten once the pack is opened. Related technologies, such as these, are an important development in helping reduce food waste. As they are not based on thermochromic inks they were not included in this background study, but many are described on WRAP's Resource Efficient Innovations Database[9].

A possible outcome from this research is to work with a retailer and supplier to develop a pilot-scale trial to establish if thermochromic inks can help consumers change their behaviour and store food appropriately, thereby getting more out of the food they buy and wasting less.

[7] http://www.freshpoint-tti.com/_userfiles/Pdf/10_Time_it.pdf

[8] http://www.youtube.com/watch?v=k0kpOoe-42g

[9] http://www.wrap.org.uk/reid

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Acknowledgements

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1.0 Introduction

Thermochromic inks are temperature sensitive materials and change colour with heat, whether from colourless to coloured, from coloured to colourless or from one colour to another colour. Each colour has a fixed temperature range and when the required temperature is reached, the colour change takes place, commonly called the activation point. The change of colour may be irreversible or reversible. Reversible inks go back through the colour scale when the heat is removed.

Thermochromic inks come in two forms: liquid crystals and leuco dyes, with leuco dyes more commonly used in packaging applications. Liquid crystals are more accurate but limited in terms of colour availability, whilst leuco dyes offer a wider range of colours. Both types of thermochromic inks are usually encapsulated to enable easier handling.

Thermochromic inks have been in the market since the 1970s, when thermochromic materials were used in 'mood rings', which changed colour according to the person's body temperature. In the food and drink sector, the technology is often used to promote a product as 'packaging theatre'.

Thermochromic inks are usually categorised as security or special effects inks, and are a niche market accounting for a small proportion of the multimillion pound packaging inks market.

Food is a valuable resource and yet UK households throw away over 7 million tonnes every year, around 20% by weight of that purchased. More than 60% (4.4 million tonnes) of this could have been eaten, including around 17 billion '5 a day' portions. Consumers spend £12 billion on food that is not eaten (13% of consumer spend on food).

Preventing this food waste could save the average family £680 a year and deliver significant environmental benefits, in terms of landfill avoidance and the mitigation of climate change. Consumers have an inherent dislike of wasting good food and want help to waste less and realise these financial savings. Equally, new research from WRAP[10] shows that how long food stays fresh for is a priority for consumers, but many are not making best use of the information on pack, or the packaging itself, to achieve this. Nor are they aware of the benefits that packaging can offer to maximise in-home shelf-life. However, there is a clear interest in packaging that can maintain food freshness, and in more effective on-pack messages about how to store food.

Food is wasted for a number of inter-related reasons, which vary depending on household characteristics. These include a lack of planning, buying more than is needed, not storing food in the right way to keep it at its best, confusion around date labelling and what food can be frozen, incorrect portioning and a lack of confidence around leftovers.

Over the last four years WRAP has built up a comprehensive evidence base[11] which has raised awareness of the issue, developed a strong case of change, and given focus to the areas where consumers need the most help, where business and local authorities can benefit, and where the biggest impacts can be made. Influencing decisions around food design, production, purchase and use is challenging, and WRAP has worked with a wide range of partners to develop a credible, integrated and consistent approach. Increasingly, WRAP is supporting people and organisations to develop their own action plans, providing them with a suite of tools and guidelines making it easier for consumers to waste less.

[10] http://www.wrap.org.uk/fresherforlonger

[11] http://www.wrap.org.uk/groceryresearch

2.0 Methodology

The methodology for this study was a staged approach involving a research phase, a stakeholder engagement phase, and a reporting phase.

During the research phase, Smithers Pira compiled a list of thermochromic inks suppliers and users in smart labels and packaging and their application within specific grocery segments. As part of the work, information was sought on available TTI technologies as these are already in use within supply chains (from food producers to retailers) and to see if, and how, thermochromic inks are used in the technology. Available pricing information was documented. How thermochromic inks were applied to products and packaging and their intended purpose were described. The mechanisms of activation and degree of sensitivity over their temperature spectrum were highlighted. In addition, information was sought relating to the durability and robustness of the ink or label with time and storage. The methods used to apply thermochromic inks were explored, including in-line application during converting or filling. The safety risks associated with using thermochromic inks and migration or food contact were explored.

The research draws upon a wide range of primary and secondary sources including industry and government reports. The research for this study covered a wide spectrum, including:

- Reviews of Smithers Pira's database of magazine and journal abstracts.
- Reviews of previous Smithers Pira reports.
- Literature and internet research.

Key stakeholders - from both suppliers and end users - were contacted to seek information in order to build up a detailed picture of how thermochromic inks were being used. Where possible, stakeholder views as to whether the inks had a role to play in helping reduce household food waste were sought.

During this stage, 20 major stakeholders were interviewed, including:

- Six suppliers of thermochromic inks and labels.
- Six Time Temperature Indicator (TTI) technology companies.
- Five major retailers and food producers.
- Three major packaging manufacturers.

The companies interviewed were 3M, Amcor, CTI (Chromatic technologies), Delta Print and Packaging, Freshpoint, Insignia Technologies Ltd, Irwins Bakery, LCR Hallcrest, LINPAC, Luminescence, M&S, Paksense, PepsiCo international, Siltech, Spear, Sun Chemical, Tesco, Timestrip, Unilever and Vitsab.

In discussions with TTI suppliers, many stated that irreversible thermochromic inks were not available at the temperatures needed to track time and temperature excursion. The study revealed that there were indeed some TTI technologies coming through to help householders reduce food waste (for instance pigments that may be activated by changes in O_2/CO_2 concentration in the pack once it is opened) but as these are not based on thermochromic inks they have not been highlighted in the main report.

This report summarises the findings.

3.0 Types of thermochromic inks

Thermochromic inks that are available in the market come in two forms:
- Liquid crystals – when activated, liquid crystal ink changes through a spectrum of multiple colours.
- Leuco dyes – the common use of the thermochromic leuco dyes in the market is to reveal an image or another colour printed beneath when activated.

Leuco dyes are more robust and less expensive compared to liquid crystals and have a greater range of inks so are more frequently used for printing in the packaging industry.

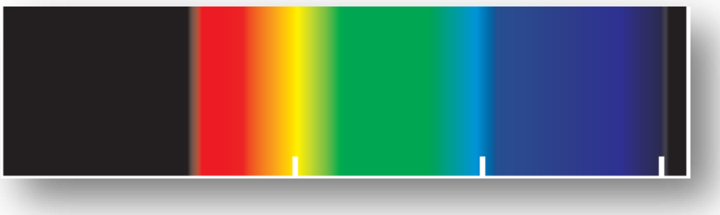
In addition, thermochromic inks can be divided on the basis of their activation temperatures:
- Low temperature thermochromic ink – when activated, changes from clear to colour, and is usually used on labels and packaging to indicate refrigeration of drinks or food products.
- High temperature thermochromic inks – when activated, changes from colour to clear, and is usually used to alert the customer to a safety hazard or when the food has reached appropriate temperate for consumption.
- Body temperature thermochromic ink – is touch activated, and is usually used for interactive graphics or packaging.

Also, the thermochromic inks are divided into:
- Reversible thermochromic inks – the colour change taken place will revert back when the temperature deviates from the activation point.
- Irreversible thermochromic inks – heat activated inks which undergo permanent change in colour when the activation temperature is reached.

3.1 Liquid crystals

Liquid crystals are clear at ambient temperatures, and, when heated, change through the rainbow spectrum of colours. The usual colour change observed with liquid crystals is from reddish brown (sometimes called tan colour) at the lowest temperatures changing to green at higher temperatures and finally reaching blue (Figure 1). The changes in colour are reversible unless the material is damaged. The colour change temperature or 'active range' for liquid crystals is -30°C to 120°C. The size of intervals at which changes are observed will depend on the composition of the material, ranging from approximately 0.5°C to 20°C. Benefitting from a short response time (usually around 10 milliseconds) and their ability to react to small temperature fluctuations, liquid crystals are suitable for applications where incremental changes of temperature over a small range need to be observed.

Figure 1 Thermochromic liquid crystals colour spectrum



Pure liquid crystals are susceptible to mechanical damage and are more difficult to work with due to their thickness, greasiness and stickiness. In order to ease the handling of the material and to prevent chemical degradation, liquid crystals are encapsulated for use in dyes and inks. Even when encapsulated, the material needs specialised equipment to be applied and is relatively expensive compared to non-thermochromic alternatives. Some examples are given in Figures 2 & 3.

Figure 2 Thermochromic liquid crystals reveal foot shape for Body Temperature Mapping

Figure 3 Thermochromic liquid crystals used in design of furniture

3.2 Leuco dyes

Leuco dyes, like liquid crystals, are usually encapsulated for easier handling, with the exception of irreversible leuco dye inks. The reversible inks microcapsule consists of leuco dye, solvent and colour developer. Sun Chemical explained that the effect observed in the thermochromic inks are down to the dye-solvent relationship "when the ink hits the [activation] temperature, the solvent evaporates dye and it loses colour".

So at ambient temperatures, the solvent is in solid state enabling the dye and colour developer to form a colour, resulting in full colour effect. At higher temperatures, the solvent is liquid, keeping colour developer and the leuco dye apart. The disappearance of colour is observed when the activation temperature is reached, which is usually between -25°C and 60°C for reversible effects, and 60°C+ for irreversible change. Sun Chemical states that they supply reversible and irreversible inks that span the temperature ranges from -9°C to 188°C. A cold activated irreversible ink is yet to be developed.

Reversible thermochromic leuco dyes are available in a wide range of colours and cover a wide range of temperatures and are available as powders, slurries, water-based, solvent-based inks and master batch. The interval of the change is approximately 3-5°C. As such, the dye is not accurate but still suitable for general indications, such as "danger, very hot". Sun Chemical explained that "thermochromic inks have a hysteresis curve, meaning that the transition [of a colour] takes place 3-5°C or 8-10°C apart", giving an example of black thermochromic ink turning grey first and then to colourless when heat is applied.

Irreversible thermochromic inks are different from reversible inks in the sense that when the colour change takes place, it is permanent. The irreversible ink changes its state from colourless to colour with activation points at very high temperatures, starting with 55°C and higher, with different temperature response curves depending on the type of colour (Figures 4 & 5). The colour range is more limited with irreversible inks compared to reversible ones, with magenta, blue and black colours available in the market. All irreversible thermochromic inks are heat activated with no available solutions for cold temperatures.

Figure **4** Example of thermochromic inks by LCR Hallcrest

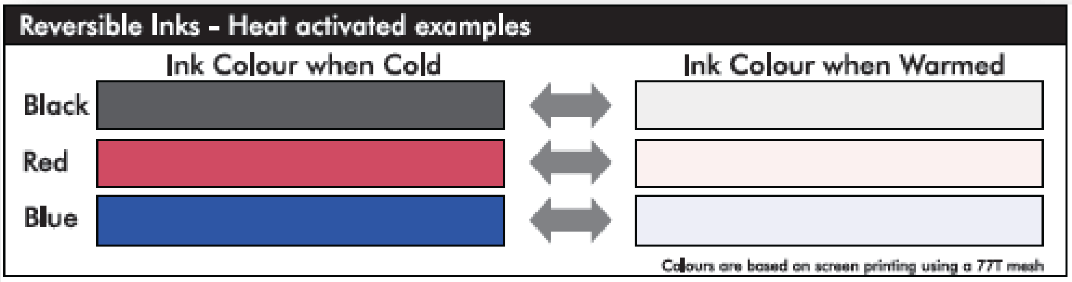
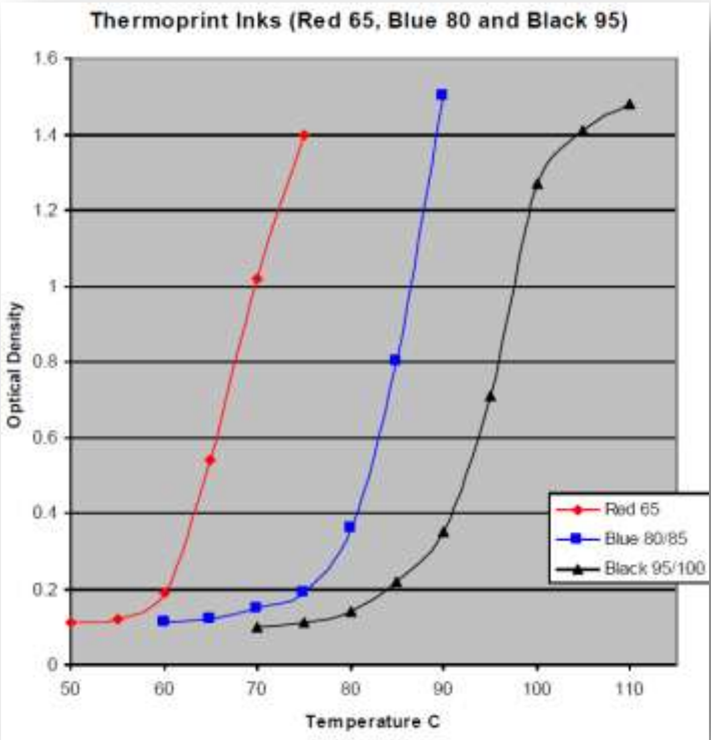


Figure 5 Temperature response curves of Thermoprint® inks produced by SILTECH



Three different activation temperatures of thermochromic inks are commonly applied in the packaging market: low refrigerator temperatures, body temperature and high temperature (usually just below the pain threshold to alert consumers). The activation temperature will depend on the end use application, and the colouring will be adjusted to the requirements of the client. For example, frozen items will have an activation temperature of -10°C, white wine at 15°C and skin contact at 28°C. Table 1 provides more detail.

Table 1 Different activation temperatures for different products proposed by Sun Chemical

Line (Sun Chemical brand name)	**Shift T°** Temperature (°C) at which colour change occurs	**Product application examples**
Arctic	-18°C	Deep-frozen items
Freeze	-10°C	Frozen items
Ice	0°C	Freezing indicator
Cold	10°C	Cold beverages
Cellar	15°C	White wine
Room	20°C	Red wine
Touch	28°C	Skin contact
Warm	40°C	Hot beverages
Hot	60°C	Depilatory waxes

4.0 Uses of thermochromic inks

Thermochromic inks have two main uses:

- Functional uses, where thermochromic ink demonstrates temperature at the time.
- Promotional, revealing a specific message and / or increasing shelf presence.

4.1 Functional uses

Functional, temperature-indicating applications are amongst the most common uses of the thermochromic liquid crystals, where the crystals are sandwiched between two layers of transparent sheet and a black or dark coloured background. The most widespread use of the sandwiched thermochromic liquids is for adhesive labels and adhesive backed thermometers.

Liquid crystals are used for thermometers to provide indicative temperature. The thermometer comprises a series of active areas, calibrated to respond to the specific temperatures, with numbers given to them to indicate the exact temperature they react to. In the example below (Figures 6 & 7), the green colour indicates that it is the exact temperature, whereas red colour indicates that the temperature is actually lower, and blue that it is higher.

Figure 6 A typical liquid crystal label structure presented by B&H Liquid Crystal Resources

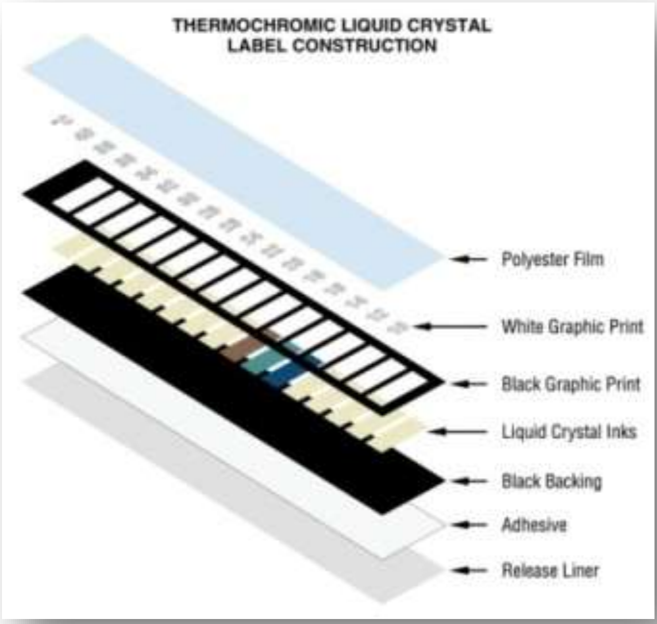
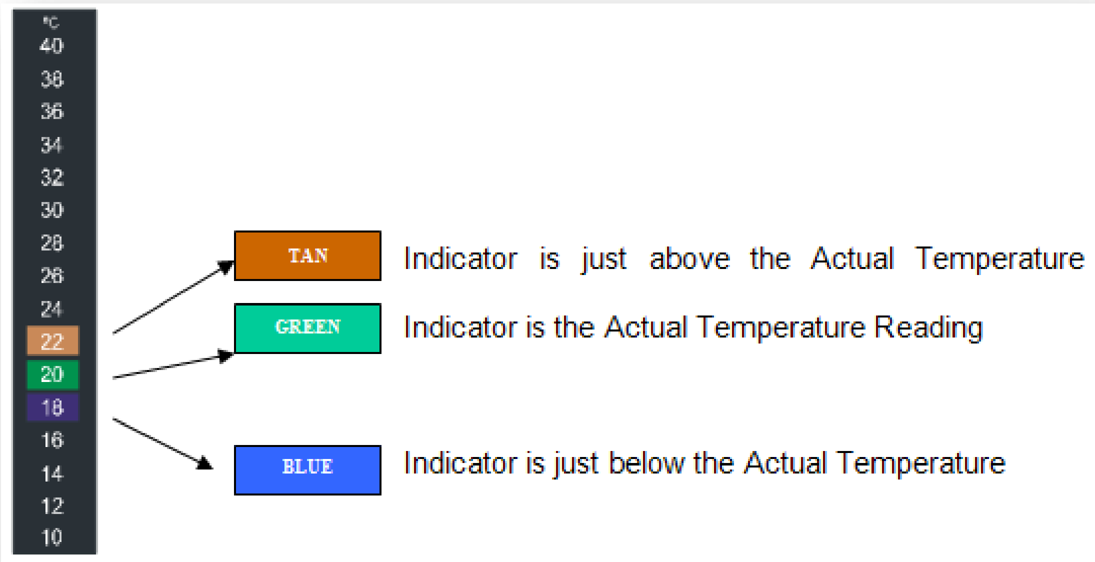


Figure 7 B&H Liquid Crystal Resources explanation of the thermochromic liquid crystal thermometer



Hallcrest has supplied major retailers with liquid crystal thermometers for their freezers and chilled food cabinets (Figure 8). These indicators quickly identify specific faults such as localised temperature problems and warm spots within a refrigeration cabinet. So the thermochromic liquid crystal thermometers show real time temperature readings to ensure food has been stored at the correct temperature. They are also used in conjunction with alarm or remote computerised temperature monitoring systems, where localised problems often do not show up on centralised digital displays, cabinet dials or computerised systems.

Figure 8 Hallcrest real time temperature indicator

Thermochromic leuco dyes are characterised by their relatively low accuracy (wide hysteresis of temperature change). Therefore, functional applications of these inks tend to be for visual or indicative purposes only. Compared to liquid crystals, thermochromic leuco dyes thermometers are usually very simplistic, developed to show whether the temperature is optimal, with the shift of colour indicating 'yes' or 'no' answers. LCR Hallcrest has developed thermometer 'labels' for fridge use to indicate when the temperature is out of range (Figure 9).

Figure 9 Hallcrest OK® Fridge thermometers indicating when the temperature in the fridge is optimal

4.2 Promotional uses

More often thermochromic leuco dyes are applied for marketing and promotional purposes, product labelling, novelty items and some applications in security printing. Examples are shown in Table 2, and those with most relevant application to food waste prevention discussed below.

Table 2 Thermochromic inks application examples in the packaging market

End Users	Product	Purpose/indicates	Description
Arrive	French poultry producer	food safety	thermometer turns red when meat is cooked properly
Ecolab	Dishwasher temperature	food safety	thermometer turns black when required temperature achieved
Fyfer	Bananas	food safety	shows if temperature is ok to keep bananas in
Jersey Diary	Milk	food safety	thermometer which shows if temperature is ok to keep product in
Lion Quality	Eggs	food safety	indicates when egg is boiled
TetraPak	Milk, juices	food safety	marks when out of date
Unnamed large supermarket	Bakery	food safety	semi-cooked bread package turns colour when bread is baked
Douwe Egberts	Chilled coffee	food safety/promotional	encourage people to keep it in the fridge as label turns colour and reveals if you won
Bloomberg	Mugs	marketing	novelty item
Hypercolour	Clothing	novelty item	novelty application
Ben & Jerry's	Ice cream	promotional	when temperature is reached reveals a code
Cadbury	Chocolate	promotional	shows when kept at the right temperature
Freschetta	Cheese	promotional	reveals a message when chilled
Haagen Dazs	Ice cream	promotional	reveals a message when chilled
Kraft food	Food	promotional	reveals a message when chilled
Mars	Chocolate	promotional	reveals a message when chilled
Metz	Beer	promotional	shows when chilled
Tetley	Tea bags	promotional	gave away thermometers to promote brand
Wired	Magazine	promotional	changes on the cover
Anheuser Busch InBev	Beer	ready to consume	shows when chilled
Bacardi	Alcoholic drinks	ready to consume	shows when chilled
Carling	Beer	ready to consume	shows when chilled
Carlsberg	Beer	ready to consume	shows when chilled
Coca-Cola	Soft drink	ready to consume	shows when chilled
Coors light beer	Beer	ready to consume	shows when chilled
Diageo	Alcoholic drinks	ready to consume	shows when chilled
Freshbake	Ready-meal	ready to consume	shows if product is hot enough
Guinness	Beer	ready to consume	shows when chilled
Heinz	Ready-meal	ready to consume	shows if product is hot enough
Hungry Jack	Maple syrup	ready to consume	shows when perfect temperature/ not too hot or cold
Jacob Creek	Wines	ready to consume	thermometer provided for appropriate temperature
Pizza Hut	Pizza	ready to consume	shows if product is hot enough
Rexam	Drink cans	ready to consume	shows when chilled
Vins De Loire	Wines	ready to consume	thermometer provided for appropriate temperature

4.2.1 Showing optimum temperature (hot)

Sun Chemical developed the application of a reversible thermochromic ink on pizza packaging to indicate that the product is hot enough to eat. When the pizza cools down, the label loses colour. The company states that consumer feedback was very positive, with many consumers aware of the label and understanding what it indicates. One of the examples of this type of pizza box is Pizza Hut RED HOT packaging (Figure 10).

Figure 10 Pizza Hut pizza packaging indicating if pizza is hot enough to eat

The thermochromic ink was used to support Pizza Hut's Hot 2 You Guarantee. If the Hot Spot does not reveal the word HOT and remains black when the customer receives their pizza order (either delivered or picked up) the customer receives a free voucher. Instructions are given on the pizza box itself, and the packaging was promoted by an extensive TV campaign. Sun Chemical confirmed that consumers valued the 'special effects' packaging; however, they may be reluctant to pay the additional price for it, as they expected the supplier or producer of the product to cover these costs.

Other examples are given in Figures 11 & 12.

Figure 11 Heat activated reversible thermochromic ink used to show whether the syrup has been heated to appropriate temperature, when reached revealing a message 'hot syrup'

Figure 12 Irreversible thermochromic inks used for Micro Chips in-pack game cards that reveal messages when microwaved with the product (when the game cards reach activation temperature, the ink permanently changes from clear to colour)

4.2.2 Showing optimum temperature (cool)

In the packaging market, the Coors glass bottle is the most famous application of a reversible thermochromic ink (Figure 13). According to Hallcrest, thermochromic inks were introduced to the package in order to encourage consumers to keep the beer chilled and consumed at its best. A thermochromic label was used where a mountain picture was changed from white to blue when the optimum (<5°C) temperature was reached.

Figure 13 Coors Light Blue mountains packages: metal can and glass bottle

According to Packaging Digest[12], Coors Light sales rose by 3% during the first year of introduction of the thermochromic labels. In addition, the use of special inks is one of the reasons why industry publication Beer Marketer's Insights observed that Coors Light displaced Budweiser as the second most sold beer in the US[13]. Hallcrest adds that the blue thermochromic ink is now closely associated with the Coors brand, meaning that competitors need to choose another colour to avoid brand confusion.

[12] http://www.packagingdigest.com/article/522552-Inkredible_interactive_innovations_.php

[13] http://adage.com/article/news/coors-light-blasts-bud-2-brew/231980/

Bacardi collaborated with Spear to develop interactive labels which use thermochromic inks to reveal wolf-claw marks (Bacardi Wolf Berry) or increased reddening (in the case Bacardi Black Razz) when chilled (Figure 14). Another example is given in Figure 15.

Figure 14 Bacardi thermochromic labels which reveal red colour when chilled

Figure 15 Cold activated reversible thermochromic ink used for Jacob's Creek packaging, revealing a message 'perfectly chilled' when the optimal consumption temperature is reached

4.2.3 Showing optimum temperature (cool) with competition incentive

Douwe Egberts used thermochromic inks to promote their new fresh chilled liquid coffee 'Cafinesse' whilst at the same time encouraging consumers to keep the fresh coffee chilled in the fridge (Figure 16). The company produced 550,000 'Chill 'n' Win' Neck Tags incorporating a thermochromic panel which, when placed in the fridge, revealed a Win message. The sampling campaign took place in selected supermarkets and was supported by TV advertising. Another example is given in Figure 17.

Figure 16 'Cafinesse' Neck Tag

Figure 17 Reversible thermochromic inks used for Budweiser beer 'Chill and Win' game cards, which display a Win message when placed on chilled bottle, which disappears when it is warming up

5.0 Application of thermochromic inks

Applications of thermochromic inks, as for any other inks, depend on the type of substrate it is going to be used on. Also, the required performance and characteristics of the print need to be considered when choosing the method of application. For example, thermochromic epoxy ink is usually screen printed on glass or fired ceramics, but also can be used for plastic, aluminium and stainless steel surfaces (epoxy ink is a type of ink produced using epoxies in order to craft strong adhesive properties, which, when the ink is dry, results in a thick, tough film). Once cured, the ink provides high resistance to detergents and abrasions and, if applied on glass, is dishwasher safe. Pad printing is also used to apply thermochromic ink to glass, fired ceramics surfaces, as well as plastic and paper substrates. Pad printing ink resistance to abrasion is lower but still satisfactory. Meanwhile, for textile substrates, screen printing is used to apply water based ink onto the material, exhibiting matt finish as well as high dry and wet fastness properties, although the print could be damaged when machine washed.

For a wide range of substrates - including paperboard, flexible and rigid plastic, plastic closures, and coated papers - screen and flexography printing technologies can be used to apply solvent based or UV cure thermochromic ink, with solvent based screen ink and UV cure screen ink exhibiting good rub resistance qualities. Meanwhile, for absorbent papers and paperboard substrates water based thermochromic ink is used, which can be printed using flexo, gravure or screen printing techniques for applications such as tickets, tags, labels and boards. In addition, thermochromic water based flexo ink exhibits good rub resistance when applied on these surfaces. Some examples are given in Figures 18, 19 & 20, more detail is given in Table 3.

Figure 18 Flexo/gravure thermochromic ink used on cold reveal label for Coca-Cola bottle to indicate when chilled

Figure 19 Thermochromic offset ink used on Wired magazine cover (January 2001 issue) activated by the body heat and when applied, changes colour from green to yellow

Figure 20 Body temperature thermochromic UV Screen Ink used for Nirvana's album cover

Table 3 The type of appropriate print ink according to the substrate it is printed on

Thermochromic Ink type	Surfaces to be printed on	Characteristics
Epoxy Screen Ink	Glass and fired ceramic; can also be printed on plastic and metals (aluminium, stainless steel)	Once cured, the print shows superior detergent and abrasion resistance. When printed onto glass, ink produces dish wash resistant print in most cases
Pad Printing ink	Substrates including plastic substrates (ABS, polyamide, polycarbonate, pre-treated polyethylene (PE) and polypropylene (PP)), paper, carton, glass and fired ceramic	Exhibits acceptable abrasion resistance properties on multiple substrates when cured in optimum conditions
Sheetfed Offset Ink	Absorbent paper and board substrates	Applications such as labels, tags, tickets and others
Solvent Based Screen Ink	A wide range of substrates including plastic (treated polyethylene and treated polypropylene, polycarbonate),	The ink exhibits good rub resistance properties

Thermochromic Ink type	Surfaces to be printed on	Characteristics
	coated papers and board substrates	
UV CureFlexo ink	A wide range of substrates including plastic (polyethylene, TC polyethylene and TC polypropylene), paper, coated papers and board substrates	Suitable for in line printing onto a wide range of substrate for applications such as labels, tags, tickets, boards providing the ink is cured (exposed to UV lamps)
UV Cure Screen Ink	A wide range of substrates including paper, plastic (polyethylene, TC polypropylene), coated papers and board substrates.	Exhibits good rub resistance properties; if a high level of resistance is required then a suitable over varnish or laminate can be used
Water Based Flexo ink	Absorbent papers and board substrates	Suitable for in line printing onto paper, carton and board substrates for applications such as labels, tags, tickets and boards; exhibits good rub resistance properties on absorbent substrates; varnish or laminate should be used if a higher level of resistance is required or if the printed product is going to be exposed to humid conditions
Water Based Gravure ink	Absorbent papers and board substrates	For applications such as labels, tags, tickets and boards
Water based textile screen ink	Textile substrates	Exhibits a matt finish when printed; the ink shows high dry and wet fastness properties as well as hand washing resistance if cured according to recommendations; cannot be machine washed
Water Based Screen Ink	Absorbent paper and board substrates	For applications such as labels, tags, tickets and boards; the prints exhibit a matt finish

The type of application also will depend on whether the ink is leuco dye or liquid crystal based. Thermochromic inks based on leuco dyes are very easy to apply with practically no difference to other packaging inks, and for reversible leuco dye inks, the same machinery can be used. The reversible inks can be printed using flexography, screen gravure, offset printing methods. Meanwhile, thermochromic liquid crystals are much more difficult to handle, so the methods of applying this kind of dye are limited to screen printing and gravure, and irreversible leuco dye inks can be just screen printed (Tables 4 & 5).

The colorant in thermochromic inks, whether it is leuco dye or liquid crystal, is usually encapsulated in relatively large capsules, ranging from 2-10 microns for leuco dyes and 10-15 microns for liquid crystals. As a result, this will affect the application of very thin layers and a thicker application is recommended to get the best effect and better resistance to UV light.

Table 4 The type of appropriate print process according to the ink type

Ink type	Water based	UV cured	Solvent	Epoxy	Offset Wet	Metal deco	Mug spray	Water based textile
Reversible leuco dyes ink	Screen, flexo, gravure	Screen, flexo	Screen, flexo	Screen	Offset	Offset	Screen	Screen
Irreversible leuco dyes ink	Screen	—	—	Screen	—	—	—	—
Thermochromic liquid crystals	Screen, gravure	—	—	—	—	—	—	—

Table 5 Application of thermochromic leuco dye inks according to Colour Change Corporation

Ink Type	Water based	UV cured	Epoxy	Plastisol
Substrates	Paper, plastics	Paper, plastics	Glass, wood	Textiles
Screen mesh	110 thread/inch	110-230 thread/inch	110 thread/inch	110-305 thread/inch
Curing	Air dry 1 hour	Expose approx. 40% longer than conventional UV ink	Air dry 7-8 hours	163°C

The type of ink printing process determines whether thermochromic ink can be laminated or overprinted:

- Epoxy screen ink - ink does not require to be overprinted or laminated, but can be used to overprint a base image.
- Pad printing ink - ink does not require being overprinted or laminated. The completely dried ink cannot be overprinted.
- Sheetfed offset ink - both heat and cold set laminates can be used; thermochromic offset inks cannot be used to overprint a base image to hide the print underneath.
- Solvent based screen ink - can be overprinted; for applications that use a thermochromic ink that is activated at cold temperatures (less than 20°C) matt laminate should be used for optimum effect.
- UV cure flexo ink and UV cure screen ink - conventional UV vure flexo inks is best overprinted with UV letterpress, UV offset and UV flexo varnish (additive may be needed).
- Water based flexo ink, water based gravure ink, water based screen ink - Both heat and cold set laminates can be used; water based flexo inks can be also overprinted with UV offset, UV flexo and UV screen varnish.

- For the UV cured and water based flexo inks used in applications using cold activated thermochromic ink (less than 20°C) matt laminate is recommended for the best effect. For warm and hot temperature activation inks (20°C and above) a gloss laminate should be used for the optimal results.

To sum up:
- There are multiple application methods of thermochromic inks and the optimal one is chosen on the basis of type of the ink and substrate it is going to be printed on.
- While reversible leuco dye based inks can be printed by the widest variety of methods, including screen, flexo, offset and gravure technologies, the irreversible inks can only be applied by screen printing.
- The liquid crystal based thermochromic inks can be applied by screen or gravure methods.
- For optimal results, varnish, overprint or laminates are sometimes recommended for the thermochromic inks.

6.0 The cost of thermochromic inks

There were conflicting views as to the economic viability of using thermochromic inks from those spoken to.

Due to the highly specialised and complicated manufacturing process, the cost of thermochromic ink is relatively expensive when compared to inks normally applied to packaging. Spear Technologies, the world's leading innovator and supplier of film pressure sensitive labelling systems, points out that the thermochromic ink is around 10 times more expensive if you compare the kilogram prices with other conventional inks.

Chromatic Technology Inks (CTI), a global supplier of thermochromic inks, lists different prices of inks according to the method of printing:
- Metal deco (mostly used for 3-piece cans) thermochromic ink: ~£233/kg
- Thermochromic offset: ~£130/kg
- Thermochromic UV Screen: ~£117/kg
- Thermochromic Flexographic or Gravure: ~£58/kg
- Thermochromic Mug Spray: ~£95/kg

Luminescence draws attention to the costs of printing rather than the ink itself. The company notes that a greater cost for the ink itself may be largely irrelevant as small amounts are used. However, specialised printing processes might be needed to print an irreversible thermochromic ink to prevent accidental activation during printing (which is not an issue for reversible inks, as they reverse back after the printing given the time to cool down). For reversible leuco dye based inks, the same printing machinery can be used as with standard printing inks.

Sun Chemical points out that with reversible thermochromic inks, the printing process is not unique and while it can be a bit more expensive, it is not disproportionately high. In this case, the company states that it comes down to the ink prices: "thermochromic inks are expensive to make, resulting in higher costs".

While there are different opinions about the key reasons for higher costs, there is a general agreement that the use of thermochromic inks leads to higher costs compared to the standard printing inks. According to CTI, the most important thing when considering additional costs of thermochromic inks is seeing the whole picture. While thermochromic inks are bit more expensive, and may have some reduced printing efficiency (e.g. if they need to be applied more thickly) while being printed, the cost of the whole package is not affected dramatically. The company points out, that inks account for very small percentage of the whole package cost, so even when thermochromic inks are 5 times more expensive, the effect will be very small. Also, the company adds that thermochromic inks are printed as standard spot colour, so any reduced efficiency will not be dramatic.

Luminescence points out that an additional '1p' cannot be put on all products; implying that any increased costs may be acceptable for the higher priced and higher end goods, but unacceptable for basic or fast moving consumer goods, which are very price sensitive. If the additional costs are passed on to the end consumers, the extra costs need to be considered carefully. Consumers are expected to tolerate the additional costs on better-quality products where the product provides them with some identifiable benefit (preferably with an option to opt-out for the cheaper product).

To sum up:

- Thermochromic inks are more expensive than the standard printing inks, but due to the small amount used on the packaging the impact on overall cost of package is small.
- Additional costs would be restricted to the ink use as the thermochromic inks would only be used where they are needed and standard or cheaper print would be used on the rest of the pack
- The printing process is very similar to standard inks for most of the thermochromic inks, for example, reversible leuco dyes can be printed using the same machinery as standard printing ink.
- Where the use of inks increases the unit price, how the product and benefits of the ink technology are positioned and marketed to consumers will impact on willingness to purchase. For example, if the consumer gets more out of the product and wastes less, they may accept a slightly higher priced product.

7.0 The robustness of thermochromic inks

Thermochromic inks have very similar handling requirements to all other packaging inks. Their shelf life depends on the ink formulation and storage conditions, as inks stored in lower temperatures tend to last longer, but on average, thermochromic inks can last from three to six months under normal conditions.

When printed, the thermochromic inks can last for years exhibiting colour change, however, extensive exposure to UV light will adversely affect the lifespan of the applied ink. CTI points out that the sensitivity to UV light is the main reason why thermochromic inks are not used on billboards or for car paint.

Ink suppliers and printers are working towards increasing the UV light resistance, for example, Siltech Ltd offers a range of UV protected thermochromic inks which claim to have a lifetime up to ten times longer than traditional thermochromic inks.

Again, as with other inks, aggressive solvents as well as extremely high temperatures of 120°C and above will negatively affect the robustness of a printed ink.

Thermochromic inks are as robust as any other printing ink when not exposed to high temperatures and UV light for extensive periods.

8.0 Safe use of thermochromic inks

Limited information appears to be publically available as to the safe use of thermochromic inks in contact with food. As with any intelligent packaging, users need to establish if the thermochromic ink has received approval from the European Food Safety Authority (EFSA) for its use in contact with food. To gain approval, EFSA carries out a safety evaluation of toxicological information and migration test data on each of the components. The process starts with documentation of all of the components and identifying those which are 'not approved' and need testing to demonstrate that migration is within prescribed limits.

Ink suppliers gave a range of views on the safe use of thermochromic inks in contact with food. Sun Chemical stated that thermochromic inks can have migration issues, and that is the main reason why they tend to be applied to glass or metal surfaces to avoid direct food contact. The company also questioned the safety of putting thermochromic inks on plastic substrates. CTI agreed that thermochromic inks should have no direct food contact: "Thermochromic inks need to have a barrier", meaning that it needs a material that stops the inks from migrating from the packaging onto the packaged food. Metal and glass are considered to be good barriers; however, paper and plastic are often thought to be insufficient in preventing the passage of ink components. On the other hand, LCR Hallcrest indicated that they are currently testing whether they can develop and provide a solution that does not require a barrier and can be printed directly on packaging.

The basis for the assurance of a high level of protection of human health and of consumers' interests in relation to food packaging (whether printed or not) is provided by Regulation (EC) No 1935/2004 concerning materials and articles intended to come into contact with foodstuffs. The responsibility of compliance with Article 3 lies with the final packaging manufacturer:

> *Materials and articles [...] shall be manufactured in compliance with the good manufacturing practice so that, under normal or foreseeable conditions of use, they do not transfer their constituents to food in quantities which could:*
> - *endanger human health; or*
> - *bring about an unacceptable change in the composition of the food; or*
> - *bring about a deterioration in the organoleptic characteristics thereof.*

GMP Regulation 2023/2006[14] also provides guidance on good manufacturing practice for materials and articles intended to come into contact with food, as all printing inks intended for use on food packaging are within the scope of this regulation. The GMP regulation lays down general rules for all business operators in the supply chain, and specifies that quality assurance and control systems are established and implemented. The Annex introduces detailed rules which relate to processes involving the application of printing inks to the non-food contact side of a material:

> *Printing inks applied to the non-food-contact side of materials and articles shall be formulated and/or applied in such a manner that substances from the printed surface are not transferred to the food-contact side:*
> - *through the substrate; or*
> - *by set-off in the stack or the reel;*
> - *in concentrations that lead to levels of the substance in the food which are not in line with the requirements of Article 3 of Regulation (EC) No 1935/2004[15].*

According to European Printing Ink Association (EuPIA), only raw materials that are included in positive lists and/or have been evaluated by a recognised expert body can be used in food contact applications. Nevertheless, EuPIA also argues that the use of non-evaluated substances does not pose a problem "as long as the relevant migration threshold of the

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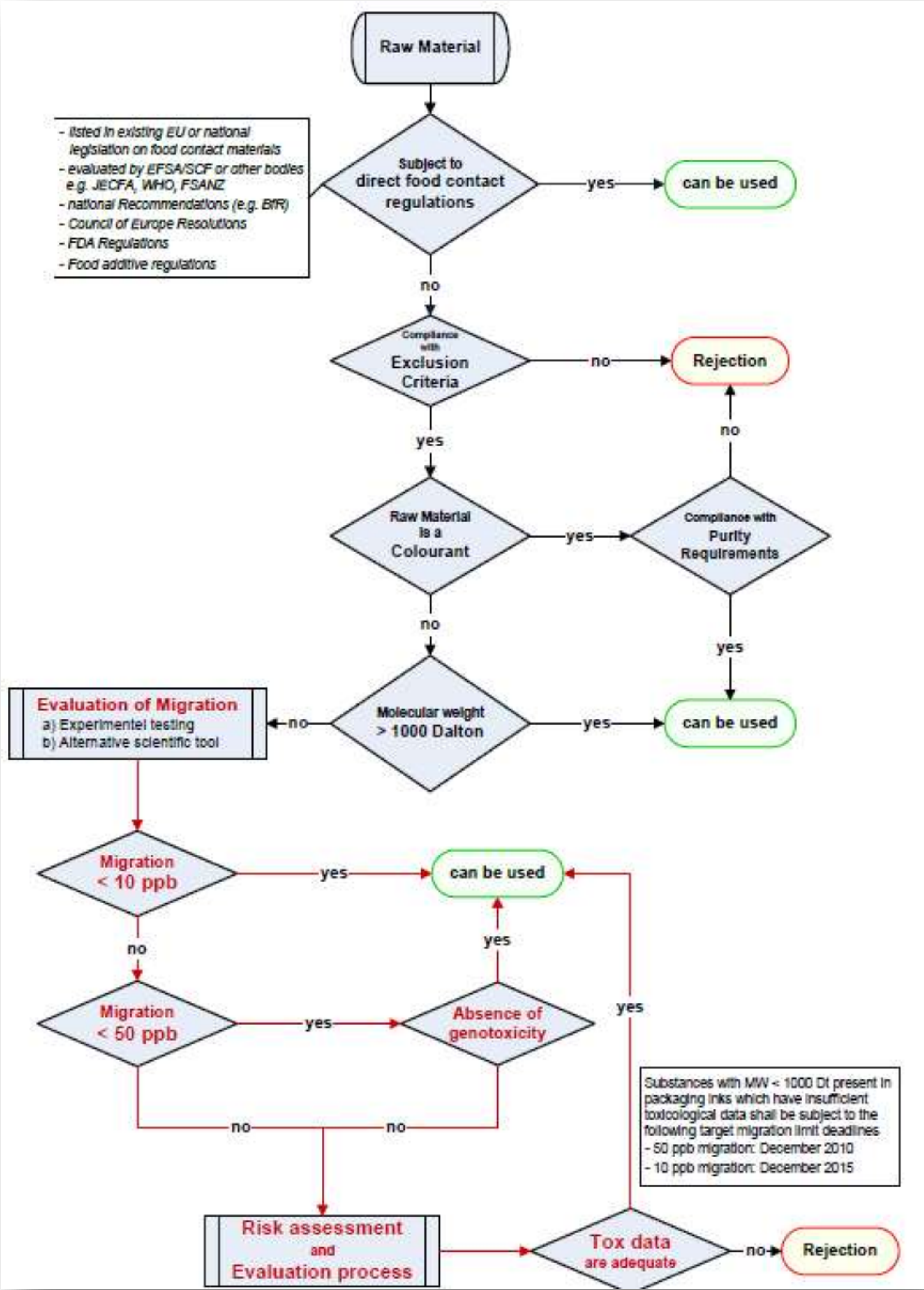
[14] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:384:0075:0078:EN:PDF

[15] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:en:PDF

substance from printed packaging into the foodstuff is met". EuPIA provides a Selection Scheme for packaging ink raw materials as guidance (which is reproduced with their permission in Figure 21).

Figure 21 Selection Scheme for packaging ink raw materials by EuPIA (November, 2011)[16]



[16] http://www.eupia.org/index.php?id=29

Siegwerk, a world-leading supplier of printing ink for packaging and publications, provides an indicative list of processes and parameters concerning design of the food packaging to avoid non-compliance (migration, organoleptic effects)[17]:

- Barrier properties of the material layers lying between ink and food – migrants from printed ink layers diffuse more and quicker the worse the barrier properties of the substrate or materials wrapping the food are.

Table 6 Barrier properties by the type of material (Siegwerk)

Poor barrier properties	Limited barrier properties	Better barrier properties	Recognized as functional barrier
Coated paper, uncoated paper, coated board, uncoated board, regenerated cellulose, polyethylene, polypropylene, ionomer, adhesive layers, printing varnish or lacquer coating layers	Polyamide, PET, polyvinylidene chloride, metallization layers	Appropriate SiOx and AlOx layers on PET, sufficiently thick layers of polypropylene	Aluminum foil, tinplate, glass; sufficiently thick layers consisting of PET or polyvinylidenechloride

- Nature of the surface which is in contact with the ink/varnish layers – after printing, within the reel or stack, invisible set-off can happen because the surface in contact with the printed layer may absorb migrants.

Table 7 Probability to set-off by the type of material (Siegwerk)

Very high probability of set-off	High set-off	Medium set-off
Coating on paper, board, aluminium, plastics; regenerated cellulose; thin extruded layers of polyethylene or polypropylene	Films or cups/tubs made of polyethylene, polypropylene, polystyrene	Uncoated paper, uncoated board, polyamide, PET

- Design of the print – a high amount of ink and primer or overprint varnishes printed per surface unit (many superposed ink layers) can increase the amount of migrants and thus enhance migration.
- Surface/volume ratio of the packaging – the higher the contact surface and the lower the volume/weight of the packed food, the more migrants may end up in the food.
- Type and nature of the packed food – food types whose nature can enhance diffusion of migrants through the substrate/packaging material and/or mobilisation of migrants present because of previous set-off.

Table 8 Probable uptake of migrants by the type of food (Siegwerk)

High uptake of migrants	Medium uptake of migrants	Low uptake of migrants
Aqueous, acid, alcoholic and/or fatty liquid food; fatty solid or liquid food in aqueous liquid food (i.e. mozzarella cheese); fatty and powdery foods; fatty and pasty foods	Aqueous pasty foods with no or minimal fat content; acidic pasty foods with no or minimal fat content; fatty and solid foods with a shape preventing full contact with the packaging (e.g. chocolate biscuit bar)	Solid and dry foods with no fat content

[17] http://www.siegwerk.com/fileadmin/user_upload/images/media_publication/RZ_Know-how_GB_120612.pdf

- Long shelf life of the packed food – the longer the food is stored, the more migrants might end up in the packed food.
- Processes to which the printed food packaging is exposed – migration increases with temperature and time.

Thermochromic inks are subject to Commission Regulation (EC) No 450/2009[18] on active and intelligent materials and articles intended to come into contact with food. The regulation lays down the requirements for active and intelligent materials:

> *Active and intelligent materials and articles:*
> - *must be suitable and effective for the intended purpose of use;*
> - *must not release to food any components in sufficient quantity as to endanger human health or to bring about an unacceptable change in the composition or organoleptic characteristics of food;*
> - *must not mislead consumers through their labelling, presentation or advertising material.*

To sum up, packaging users need to seek regulatory guidance and undertake specific testing in order to make sure that the thermochromic inks (as any other inks) are compliant with direct food contact use. The European Commission maintains a database on Food Contact Materials[19]. This database is a tool to inform about the substances to be used in materials and articles intended to come into contact with food (Food Contact Materials).

9.0 Conclusion

Reversible thermochromic inks have the potential to provide the consumer with 'dynamic information' about the current temperature of the product; for instance, if a product is left out of the fridge and is beginning to warm up. They could, therefore, play a role in reducing household food and drink waste by alerting consumers that a product is not being stored at the correct temperature. The label could change from indicating "I'll last longer" when cold to "I'm ready to eat" at ambient temperatures. Alternatively, this idea could be adapted to trigger new storage behaviour through a single 'reveal' message. For example, a label on an apple pack could say "refrigerate to reveal my secret message" and when cold reveal a message of "apples will stay fresh twice as long if kept in the fridge". If this type of label is accompanied by marketing, explaining what consumers should look for, it may help lead to behaviour change.

Thermochromic inks based on leuco dyes are very easy to apply with practically no difference to other packaging inks, and for reversible leuco dye inks, the same machinery can be used. They are more expensive than normal inks to buy, but as small quantities are used they have little effect on costs of overall packaging. When printed, the thermochromic inks can last for years exhibiting colour change; however, extensive exposure to UV light will adversely affect the lifespan of the ink. Packaging users need to seek regulatory guidance and undertake specific testing in order to make sure that the thermochromic inks (as any other inks) are compliant with direct food contact use, and this report highlights examples of where these inks are already in use.

A possible outcome from this research is to work with a retailer and supplier to develop a pilot-scale trial to establish if thermochromic inks can help consumers change their behaviour and store food appropriately thereby getting more out of the food they buy and wasting less.

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[18] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:135:0003:0011:EN:PDF

[19] https://webgate.ec.europa.eu/sanco_foods/main/?event=display

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