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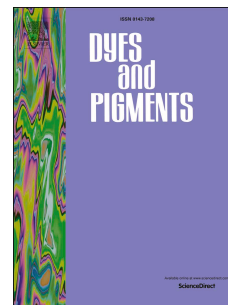


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Stephen M. Burkinshaw, George Salihu



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1 **The role of auxiliaries in the immersion dyeing of textile fibres: Part 1 An** 2 **overview**

3 ***Stephen M Burkinshaw and George Salihu**

4 s.m.burkinshaw@leeds.ac.uk; g.salihu@leeds.ac.uk

5 University of Leeds, Leeds, LS2 9JT, UK

6 *corresponding author

7

8 **Abstract**

9 Although auxiliaries have been a key component of immersion dyeing processes for many years the
10 precise mode of action of many auxiliaries has not been fully resolved. This part of the paper
11 discusses the various types of auxiliary available and the nature of the assistance they provide in
12 immersion dyeing processes, together with both environmental and financial aspects associated
13 with their use, as well as a discussion of the relationship between liquor ratio and the use of
14 auxiliaries in immersion dyeing.

15

16 **Highlights**

- 17 • there are many different types of dyeing auxiliary
- 18 • they are chemically diverse and perform many essential operations
- 19 • the precise mode of action of many auxiliaries is unclear

20

21 **keywords**

22 fibres; auxiliaries; dyeing; finishing

23

24 **abbreviations**

25 PA: polyamide; PES: poly(ethylene) terephthalate; COD: Chemical Oxygen Demand; BOD₅

26 Biological Oxygen Demand; TDS: Total Dissolved Solids

27 **1 Introduction**

28 By some margin, water is the most commonly used medium for the dyeing of textile materials, with
29 *air* being employed in the *vapour-phase dyeing* of hydrophobic fibres and both non-aqueous *liquid*
30 *solvents* and non-aqueous *supercritical fluids* having attracted only small-scale, mostly niche
31 interest (1). This paper concerns the application of dyes to textile fibres from *aqueous dyebaths*
32 using *immersion* processes (aka *batchwise* -, *exhaust* -, *long liquor*- processes) and the role of the
33 many and varied *auxiliaries* which are used in such dyeing processes.

34

35 In this context, an auxiliary can be defined as *a chemical or formulated chemical product which*
36 *enables a processing operation in preparation, dyeing, printing or finishing to be carried out more*
37 *effectively or which is essential if a given effect is to be obtained* (2). Such *auxiliaries*, which often
38 are referred to as *dyeing auxiliaries*, are extensively utilised in immersion dyeing for all dye-fibre
39 systems (eg disperse dyes/polyester, reactive dyes/cotton, acid dyes/wool, etc.); indeed, auxiliaries
40 are commonly viewed as essential components of such dyeing process. Auxiliaries are also widely
41 used in *continuous dyeing* (aka *padding processes*) and, whilst some auxiliaries are specifically
42 intended for use in either batchwise or continuous dyeing, many auxiliaries can be used in both
43 types of process.

44

45 **2 auxiliaries used in dyeing**

46 Accounts of auxiliaries that are used in dyeing, as well as in other aspects of textile wet processing,
47 are available [eg (3-14)]. By way of brief introduction, auxiliaries assist the dyeing process, but
48 usually in a very particular way, insofar as the assistance furnished by a given auxiliary will typically
49 address a specific aspect of dyeing, such as fibre wetting, dye-fibre substantivity, dye levelling, fibre
50 protection, etc. As such, a wide variety of different types of dyeing auxiliary is available (eg
51 dispersants, sequesterants, lubricants, etc.); furthermore, owing to the diverse, and often quite
52 specialised, nature of the assistance they exert, auxiliaries comprise a heterogeneous group of
53 chemicals (eg acids, surfactants, reductants, etc.), as illustrated by the data presented in Table 1.
54 Although many dyeing auxiliaries may have one primary function and comprise an individual

55 compound, others may fulfil more than one role, and many commercial auxiliary products often are
 56 proprietary mixtures that contain several components. Auxiliaries therefore include simple chemicals
 57 such as inorganic salts (eg NaCl, etc.), lye (eg NaOH), acids (both organic such as CH₃COOH and
 58 inorganic such as HCl, etc.), reducing and oxidising agents (eg Na₂S₂O₄, H₂O₂, etc.), as well as
 59 oligomers, polymers and a wide variety of surfactants.

60

61 Table 1 overview of auxiliaries employed in dyeing, their effects and chemical composition (15)

62

process	auxiliary	effect	chemical type
dissolving dyes	dye solubilising agents; hydrotopes	promote dissolution of dyes in water	alcohols; polyols; fatty alcohol ethoxylates; esters naphthalene sulfonic acid formaldehyde condensates; naphthalene sulfonates;
	dispersing agents; protective colloids	promote formation and stability of dye dispersions	lignosulfonates; fatty alcohol ethoxylates; alkylsulfonates; alkylaryl sulfonates; polyacrylates
exhaust dyeing	wetting agents; deaeration agents	increase wetting capacity of the dye liquors; increase dye adsorption	alkylsulfates; alkanesulfonates; alkylarylsulfonates; salts of sulfosuccinic acid; esters; fatty alcohol ethoxylates; alcohols; phosphoric acid esters; hydrocarbons
	dye protecting agents; boil-down protecting agents	protect dyes during application	buffers and/or oxidants (nitrobenzene sulfonate); urea; alkylarylsulfonates
	oxidising agents	oxidise reduced forms of vat and sulphur dyes; strip dyes and auxiliaries from the fibre	peroxo compounds; sodium perborate; sodium persulfate; sodium chromate; salts of <i>m</i> - nitrobenzene sulfonic acid; bromite; sodium chlorite

		sodium dithionite; sulfonic acid
reducing agents	reduce vat and sulphur dyes; reduction clearing; dye stripping	derivatives; sodium sulphide; glucose and mixtures thereof; thiourea dioxide; sodium or zinc formaldehyde sulfonic acids
brightening agents	partial removal of adsorbed dye	polyvinylpyrrolidone; polyglycol ether; cellulases; alkyl aryl sulfonates; alkyl amine ethoxylates; reducing agents and oxidising agents
fibre-protective agents	prevent or reduce fibre damage during dyeing	protein hydrolysates; polyglycol ether; protein fatty acid condensates; lignosulfonates; formaldehyde eliminating products (urea derivatives); guanidine derivatives; benzophenones; benzotriazoles
mordants	improve dye fastness	Al, Cr, Fe salts
pH-regulators; acids and alkali dispensers	pH adjustment/control	organic acids; esters; buffers
acids and alkalis	pH adjustment	organic acids (mainly acetic acid, formic acid, oxalic acid), inorganic acids (sulfuric acid, hydrochloric acid); sodium hydroxide; ammonium hydroxide; sodium carbonate
salts	increase dye substantivity	sodium chloride; sodium sulfate
complexing agents	complexation of heavy metals	polyphosphates; phosphonates; polycarboxylates, (polyacrylates, polyacrylate- maleinic acid copolymers); sugar copolymers; hydroxycarboxylic acids; amino carboxylic acids

exhaust dyeing: PES; PES/WO	carriers	accelerate dye adsorption, dye diffusion	aromatic hydrocarbons; chlorinated aromatic compounds; benzoic acid esters; phthalic acid esters; alkyl phthalimides; alkylphenoethoxylates
levelling	retarding agents; migration agents; penetrating agents	promote even distribution of dye	alkyl -; alkyl aryl -; alkyl amine -; and alkyl aryl amine ethoxylates; fatty acid esters and amides; fatty acid condensates; polyvinyl pyrrolidone; quaternary ammonium compounds; alkyl sulfates; alkyl aryl sulfonates
aftertreatment	fastness improvement agents	improve rubbing, wet and light fastness	aftertreatment with detergents or polymers; cationic fixing agents; polysulfonates for PA dyed with anionic dyes; organic copper compounds for PA and PES fibres

63

64 A large number of commercial auxiliary products are available, as exemplified by a 2008 publication
65 (16) that lists >6500 commercial products derived from 400-600 active compounds. Consumption of
66 dyeing auxiliaries is estimated to be 60-70% of that of dyes (12), which, in 2012, would have
67 corresponded to 0.96–1.2 x 10⁶ T of auxiliary consumed in textile dyeing, according to an estimated
68 global dye consumption of 1.6 x 10⁶ T (1). However, auxiliary usage varies according to several
69 factors, such as the particular dye-fibre system employed, depth of shade of the dyeing, machine
70 type, liquor ratio employed (a detailed account of liquor ratio is presented in section 5), etc., as
71 illustrated by Table 2, which shows some of the types of auxiliary that can be employed in the
72 immersion dyeing of different types of fibre and, also, by the data displayed in Table 3, which
73 presents typical types and amounts of auxiliary utilised in the dyeing of knitted cotton fabric with
74 reactive dyes.

75

76 Table 2 auxiliaries that can be used in the immersion dyeing of different types of fibre

process	auxiliary	effect	chemical type
---------	-----------	--------	---------------

dissolving dyes	dye solubilising agents;	promote dissolution of dyes in	alcohols; polyols; fatty alcohol ethoxylates;
	hydrotopes	water	esters
dissolving dyes	dispersing agents;	promote formation and stability	naphthalene sulfonic acid formaldehyde
	protective colloids	of dye dispersions	condensates; naphthalene sulfonates; lignosulfonates; fatty alcohol ethoxylates; alkylsulfonates; alkylaryl sulfonates; polyacrylates
wetting agents; deaeration agents		increase wetting capacity of the dye liquors; increase dye adsorption	alkylsulfates; alkanesulfonates; alkylarylsulfonates; salts of sulfosuccinic acid; esters; fatty alcohol ethoxylates; alcohols; phosphoric acid esters; hydrocarbons
	dye protecting agents; boil-down protecting agents	protect dyes during application	buffers and/or oxidants (nitrobenzene sulfonate); urea; alkylarylsulfonates
oxidising agents		oxidise reduced forms of vat and sulphur dyes; strip dyes and auxiliaries from the fibre	peroxo compounds; sodium perborate; sodium persulfate; sodium chromate; salts of <i>m</i> - nitrobenzene sulfonic acid; bromite; sodium chlorite
	exhaust dyeing	reduce vat and sulphur dyes;	sodium dithionite; sulfonic acid
reducing agents		reduction clearing; dye stripping	derivatives; sodium sulphide; glucose and mixtures thereof; thiourea dioxide; sodium or zinc formaldehyde sulfonic acids
	brightening agents	partial removal of adsorbed dye	polyvinylpyrrolidone; polyglycol ether; cellulases; alkyl aryl sulfonates; alkyl amine ethoxylates; reducing agents and oxidising agents
fibre-protective agents		prevent or reduce fibre damage during dyeing	protein hydrolysates; polyglycol ether; protein fatty acid condensates; lignosulfonates; formaldehyde eliminating products (urea derivatives); guanidine derivatives; benzophenones; benzotriazoles

mordants	improve dye fastness	Al, Cr, Fe salts
pH-regulators; acids and alkali dispensers	pH adjustment/control	organic acids; esters; buffers
acids and alkalis	pH adjustment	organic acids (mainly acetic acid, formic acid, oxalic acid), inorganic acids (sulfuric acid, hydrochloric acid); sodium hydroxide; ammonium hydroxide; sodium carbonate
salts	increase dye substantivity	sodium chloride; sodium sulfate
complexing agents	complexation of heavy metals	polyphosphates; phosphonates; polycarboxylates, (polyacrylates, polyacrylate-maleinic acid copolymers); sugar copolymers; hydroxycarboxylic acids; amino carboxylic acids
exhaust dyeing: PES; PES/Wool	carriers accelerate dye adsorption, dye diffusion	aromatic hydrocarbons; chlorinated aromatic compounds; benzoic acid esters; phthalic acid esters; alkyl phthalimides; alkylphenoethoxylates
levelling	retarding agents; migration agents; penetrating agents promote even distribution of dye	alkyl -; alkyl aryl -; alkyl amine -; and alkyl aryl amine ethoxylates; fatty acid esters and amides; fatty acid condensates; polyvinyl pyrrolidone; quaternary ammonium compounds; alkyl sulfates; alkyl aryl sulfonates
aftertreatment	fastness improvement agents improve rubbing, wet and light fastness	aftertreatment with detergents or polymers; cationic fixing agents; polysulfonates for PA dyed with anionic dyes; organic copper compounds for PA and PES fibres

78

79

80 Table 3 Typical requirements for immersion dyeing of knitted cotton fabric with reactive dyes (15)

81

component /g kg ⁻¹ textile	light shade	medium shade	dark shade
dye	0.5-4	5-30	30-80
organic auxiliary	0-30	0-30	0-35
inorganic auxiliary	50-250	30-150	30-150
salt	90-400	600-700	800-2000

82

83 *2.1 the nature of the assistance afforded by auxiliaries*

84 The principal aims of all immersion dyeing processes are to produce uniform dyeings of the desired
85 colour and depth of shade that display the required level of fastness to specified agencies (eg
86 washing, light, etc.). Of these (and other) characteristics sought in a dyed material, uniformity is
87 perhaps of greatest importance, because, if a dyeing is unlevel, then regardless of its colour, depth
88 of shade or fastness properties, it is most likely unsaleable. In this context, dyes vary, considerably,
89 in their ability to migrate during dyeing and thereby, to furnish level dyeings. Although such
90 migration ability is an inherent characteristic of a given dye and, often, a particular dye-fibre system,
91 dye migration during immersion dyeing can be conveniently manipulated by controlling the level of
92 dye-fibre substantivity within the dyeing process. As dye-fibre substantivity comprises both
93 mechanical and physico-chemical elements, the level of dye-fibre substantivity within exhaust
94 dyeing procedures can be adjusted by controlling machine-dependent factors (eg rate and extent of
95 dye-substrate interchange, heating rate, etc.) and by manipulating both the nature and extent of
96 dye-dye and dye-substrate interactions within the dyebath via, for example, pH adjustment,
97 temperature control, selection of liquor ratio, and, of relevance to this paper, the use of auxiliaries.

98

99 In virtually all immersion dyeing processes, a 'base' level of dye-fibre substantivity control is
100 commonly employed using simple chemicals, such as inorganic acids or buffer systems (eg

128 fibres, inorganic electrolytes such as NaCl or Na₂SO₄ are used to promote dye exhaustion and, in
 129 the case of reactive dyes, to promote dye fixation.

130

131 A x gl⁻¹ NaCl or Na₂SO₄

132 2 gl⁻¹ *Ladiquest 1097 liq*

133 1 gl⁻¹ *Imacol C3G liq*

134 1 gl⁻¹ *Humectol C liq hc*

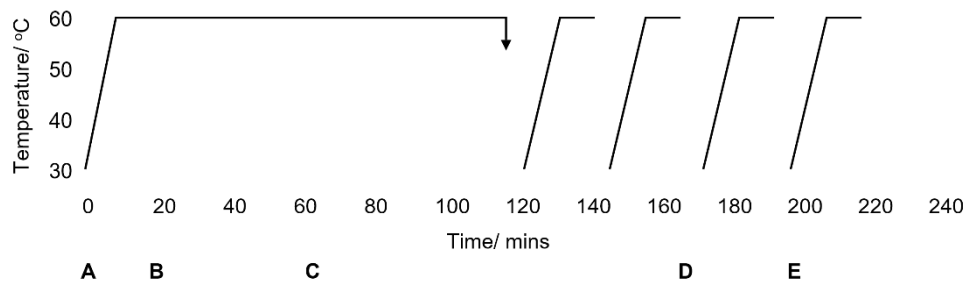
135 B *Drimaren HF dye*

136 C NaHCO₃

137 D 1 gl⁻¹ *Ladiquest 1097 liq*

138 1 gl⁻¹ *Ladipur RSK liq*

139 E neutralisation (pH 6-7)



136 Figure 2 dyeing and wash-off process for *Drimaren HF* reactive dyes (17)

137

138 In each of these dye-fibre systems, the promotional effects imparted by the added inorganic
 139 electrolyte during dyeing are non-permanent insofar as, at the end of dyeing, the electrolyte is
 140 removed, which is of especial importance in the case of the wash-off stages that are employed in
 141 the immersion dyeing of cellulosic fibres with reactive dyes. In a similar manner, carriers are
 142 sometimes used to promote the sorption and levelling of disperse dyes on PES fibres but the
 143 specific promotional effect imparted by the carrier is non-permanent and their complete removal
 144 from the dyed substrate at the end of dyeing is essential in order for the dyed samples to display
 145 optimum fastness to various agencies. In contrast, auxiliaries that are specifically employed to
 146 improve the fastness properties of dyeings, such as fixing agents (aka cationic fixing agents) which
 147 impart improved wet fastness to direct dyes on cellulosic fibres, or UV absorbers which provide
 148 improved protection towards fading by light, must remain within the dyed substrate in order for their
 149 impact to be achieved. In some cases, as exemplified by the use of reducing agents in the
 150 application of sulphur dyes to cellulosic fibres, the auxiliary is an indispensable, essential
 151 component of the dyeing process; in this particular case, the reducing agent converts the water-
 152 insoluble colorant into the fibre-substantive, water-soluble, thiol derivative that is adsorbed by the
 153 fibre.

154

155 3 environmental aspects associated with the use of dyeing auxiliaries

156 Although water is often considered as a renewable resource owing to its replenishment by rainfall,
157 the total volume of water on earth is, of course, constant and, therefore, its availability for industrial,
158 agricultural and urban usage, is finite. Furthermore, as both the freshwater resources available
159 globally and the world's population are distributed unevenly, water shortages exist in many regions.
160 Such a situation can be expected to only worsen, as an expanding global population, continued
161 urban growth, rising industrialisation and increased food production place demands on the finite
162 global supply of water.

163

164 Although water is of fundamental importance in immersion dyeing, the amount of water employed
165 varies, according to, for example, the type of machine used, the type of fibre used, the physical form
166 of the fibre, type of dye, etc. Whilst precise figures are not available for global water usage in
167 dyeing, an indicative estimate has been proposed (1) based on global textile fibre consumption and
168 assuming an average liquor ratio of 1:8 for dyeing and a cumulative average 1:10 liquor ratio for wet
169 processes associated with dyeing (eg wetting, rinsing, wash-off, etc.). Using this approach, in 2015,
170 as world textile fibre production totalled 90.64×10^6 T (19), of which PES fibres accounted for ~59%
171 (53.1×10^6 T) and cotton & man-made cellulosic fibres ~31% (28.1×10^6 T), the amount of water
172 used in dyeing (assuming that all fibre production was dyed) would have been of the order of $16.3 \times$
173 10^{11} l, of which 9.6×10^{11} l can be ascribed to that of PES dyeing and 5.1×10^{11} l to the dyeing of
174 cotton and other cellulosic fibres. However, as pointed out (1) such an estimated level of water
175 consumption, which corresponds to 18 l per kg of fibre, may be somewhat modest, when compared
176 to reported water usage in commercial dyeing processes, such as the 72-96 l kg⁻¹ of water
177 consumed in typical batchwise jet dyeing processes (20) or that used in the batchwise, immersion
178 dyeing of cotton with reactive dyes (Table 4 and Table 5) (21).

179

180 Table 4 Water, chemicals and energy consumed in jet dyeing of cotton using reactive dyes (21)

181

process	dye	
	<i>Novocron FN</i>	<i>Remazol RGB</i>
preparation	scour/bleach: 98°C	scour/bleach: 98°C
	rinse: 80°C	rinse: 80°C
	rinse: 60°C	rinse: 60°C
	migration	
dyeing	dyeing: 80/60°C	isothermal dyeing: 60°C
wash-off	rinse: 50°C	rinse: 50°C
	rinse: 70°C	rinse: 50°C
	boil off	rinse: 80°C
	rinse: 80°C	boil off
	rinse: 60°C	rinse: 80°C
	rinse: 50°C	rinse: 25°C
process time/ mins	691	649
water consumption/ l	dyebath water	16400
	cooling water	16380
	total	32000
	per kg of fibre	160
energy consumption/ MJ	total	3974
	per kg of fibre	19.87
chemicals consumed/ kg	total	253
	per kg of fibre	1.27
dyes consumed/ kg	total	5.55
	per kg of fibre	0.028

182

183 *assumptions made in Table 4:*184 *200 kg fibre; 10:1 liquor ratio; cold water at 20°C; no hot fill (all heating done in machine); liquor retention: 2x mass of fibre*185 *on draining; standard fill / drain; no parallel rinsing/draining; 100% right first time (no additions); all hot baths cooled to*

186 60°C before draining; 50% efficiency of heating (steam energy transfer); 50% efficiency of cooling (heat transfer to cold
 187 water); no water recycling; no use of renewable energy

188

189 Table 5 jet dyeing machine: steam and water consumption; reactive dyes; 100% cotton (22)

process	steam used/ kg kg ⁻¹ fibre	water used/ l kg ⁻¹ fibre
bleach, light biowash without enzyme stop, extra dark shade with HT drain	2.93	36.17
bleach, <i>Remazol Ultra RGB</i> , dark red	2.8	48.13
bleach, <i>Drimaren CL</i> , medium shade with HT drain	1.77	35.18
bleach at 95°C, biowash, light shade 60°C without HT drain	2.34	38.25

190

191 Such data clearly shows that very large amounts of water are utilised in immersion dyeing. It is,
 192 therefore, perhaps unsurprising, that immersion dyeing processes routinely generate very large
 193 amounts of wastewater, as exemplified by the finding (23) that in the Indian city of Tirupur, dyeing
 194 and bleaching plants generated 87,000 T of wastewater per day. Unfortunately, such high levels of
 195 water consumption and wastewater generation in dyeing is not especially remarkable when it is
 196 recalled that immersion dyeing is only one of several wet processes that are used in the conversion
 197 of raw materials into finished textile products and, also, that the textile industry characteristically
 198 consumes extraordinarily large amounts of water and generates vast amounts of wastewater. For
 199 example, it is reported that in the Indian textile industry, each 200 kg of water per kg of textile that is
 200 consumed in textile manufacture results in 200–350 kg of wastewater generation per kg of finished
 201 product (24).

202

203 In view of the previously mentioned high levels of auxiliary consumption in dyeing, the wastewater
 204 created during immersion dyeing is likely to contain a wide variety of auxiliary chemicals. Indeed, as
 205 many of the auxiliaries that are employed in immersion dyeing are intended to be removed from the
 206 dyed material at the end of dyeing, such chemicals will be present in the wastewater that ensues

207 from dyeing processes [eg (8, 10, 25)]. This is illustrated by the data presented in Table 6 which
 208 shows the low contribution that both dye and UV absorber make towards wastewater *chemical*
 209 *oxygen demand (COD)* as these particular components of the disperse dye/PES dyeing system are
 210 intended to be adsorbed by the substrate.

211

212 Table 6 Typical input and calculated output factors for the exhaust dyeing of PES knitted fabric using disperse

213 dyes (1:10 liquor ratio) (26)

214 using disperse dyes (1:10 liquor ratio) (27)

215

process	component	input factor/ g COD kg ⁻¹ textile	output factor: emission to wastewater/ g COD kg ⁻¹ textile
dyeing	dye	1-100	0.5-50
	dispersing agent	6	5
	carrier	23	11
	UV absorber	19	4
	defoaming agent	17	16
aftertreatment	reducing agent	7	5
	sequestrant	3	3

216

217 *Notes to Table 6:*

218 1. *as disperse dye formulations contain 40-60% dispersing agents, the output factor is 0.5-50;*

219 2. *as very small amounts of dispersing agent and defoaming agent remain on the textile, they reach wastewater*
 220 *nearly quantitatively;*

221 3. *as carriers are substantive towards PES fibres, ~50% remains on the substrate;*

222 4. *UV absorber is substantive towards PES fibres and only ~20% reach wastewater;*

223 5. *as reducing agents are partially oxidised (30% assumed), COD contribution to wastewater is lower than the input.*

224

225 The wastewater obtained from immersion dyeing processes varies, in terms of both volume and
 226 composition, depending on factors such as, for example, the type of fibre being dyed and its

227 physical form, the class of dye used, the nature of the dyeing machine employed, etc., as well as
228 the particular water management philosophy in use. Dyeing wastewater is invariably highly
229 coloured, contains various types of both organic and inorganic compounds (see Tables 1 and 2 for
230 chemicals that could be present), and displays typically high values of COD, *biological oxygen*
231 *demand (BOD₅)*, *total suspended solids (TSS)* and *total dissolved solids (TDS)*.

232

233 Although dyeing wastewater is subjected to some form of effluent treatment, because the
234 wastewater from dyeing processes characteristically displays marked resistance towards
235 biodegradation (27, 28), such treatment is, typically, not only complex but also entails substantial
236 expenditure of time, energy and chemicals. Although many strategies have been explored for
237 treating dyeing effluent including both traditional treatment methods, such as adsorption, filtration
238 and coagulation, as well as oxidation, biological degradation, photocatalysis, biosorption and low-
239 cost adsorbents [see for example (24, 25, 29-36)], no single treatment method has yet been
240 developed which can deal with the complex and varied nature of dyeing wastewater. Furthermore,
241 the impact of dyeing auxiliaries on the effectiveness of wastewater decolourisation and re-use has
242 received attention [eg (37-39)], as has the toxicity of auxiliaries used in reactive dyeing (40), whilst
243 the environmental impact of surfactants is a well-discussed area [eg (41-44)].

244

245 Clearly, from an environmental perspective, the less water used in immersion dyeing the better.

246

247 3.1 reactive dyes and cellulosic fibres

248 An example of the scale of the environmental challenges posed by the routine usage of auxiliaries in
249 dyeing processes is provided by reactive dyes that are used in the dyeing of cellulosic fibres such
250 as cotton, lyocell, rayon, etc. Reactive dyes are one of five classes of dye (direct dyes, sulphur
251 dyes, vat dyes, azoic colorants and reactive dyes) that can be used to dye cotton and other
252 cellulosic fibres using immersion dyeing processes. Owing to their world-wide popularity, reactive
253 dyes nowadays account for around ~55% of global dye consumption for cellulosic fibres. An
254 estimate can be made of the scale of this usage based on published statistics for world fibre

255 production and assuming an average of 2% on mass of fibre dye is employed for exhaust dyeing
 256 (1). Accordingly, in 2015, as world cotton & man-made cellulosic fibre production was $28.1.6 \times 10^6$ T
 257 (19) than ~300,000 T of reactive dyes would have been used to dye cellulosic fibres. Despite the
 258 very large global popularity of reactive dyes for cotton and other cellulosic fibres, their usage in
 259 immersion dyeing processes presents manifold environmental challenges that arise because of the
 260 inherent inefficiency of the exhaust reactive dyeing process.

261
 262 By way of explanation, for any dye-fibre system, all of the dye that is applied to the textile substrate
 263 during immersion dyeing should, ideally, be physically and/or chemically retained by the substrate.
 264 The proportion of dye originally applied to a substrate that remains on the substrate after exhaust
 265 dyeing and associated processes, is referred to as dye *fixation* (1). In practice, 100% dye fixation is
 266 rarely achieved in immersion dyeing, as demonstrated by the data shown in Table 7; in this context,
 267 it has been estimated that $\sim 2 \times 10^5$ T of the dyes produced annually are lost during dyeing and
 268 finishing because of inefficient dyeing procedures (45). Levels of dye fixation vary for different dye-
 269 fibre systems (Table 7), with that typically achieved for reactive dyes on cellulosic fibres being
 270 characteristically low.

271

272 Table 7 Estimated dye fixation achieved for different dye/fibre combinations (46)

dye/fibre combination	fixation/%
basic/PAN	97-98
pre-metallised acid/wool	93-98
azoic colorants/cellulose	90-95
disperse/PET	80-98
direct/cellulosic	80-95
vat/cellulosic	80-95
non-metallised acid/wool/PA	80-93
sulphur/cellulosic	60-70
reactive/cellulosic	50-80

273

274 For all dye-fibre systems, at the end of exhaust dyeing, unfixed, vagrant dye molecules must be
 275 removed from the dyed material, which otherwise, will desorb from the dyeing during subsequent
 276 use (eg domestic laundering), resulting in colour change and staining of adjacent materials.
 277 Although a rinse using cold water is the most rudimentary removal process that can be used, such a
 278 simple water rinse is seldom able to remove all residual dye. Thus, a more rigorous process,
 279 referred to generically as *wash-off*, is employed, which commonly takes the form of successive
 280 aqueous treatments which utilise progressions of cold/warm/hot water baths together with
 281 specialised, proprietary auxiliaries to expedite dye and auxiliary removal. In this context, the wash-
 282 off of reactive dyes on cellulosic fibres is of especial significance from a wastewater perspective.

283

284 Reactive dyes are so named because they can 'react' with appropriate groups within the cellulosic
 285 fibre and, therefore, form a covalent bond with substrate (the dyes can also covalently bind to other
 286 types of fibre that contain suitable nucleophilic groups, such as PA, silk and wool). To achieve this,
 287 reactive dyes are applied to cotton and other cellulosic fibres under aqueous alkaline (eg NaOH,
 288 Na₂CO₃) conditions so that electrophilic groups in the dye can form a covalent bond with the more
 289 strongly nucleophilic, ionised hydroxyl groups (Cell-O⁻) that are generated within the substrate under
 290 alkaline conditions, rather than the less nucleophilic cellulosic hydroxyl groups (Cell-OH).
 291 Unfortunately, such aqueous alkaline application conditions result not only in covalent bond
 292 formation with the substrate but also alkali-induced hydrolysis of the reactive dye. Thus, all
 293 commercial reactive dyes display inherently low levels of dye-fibre fixation efficiency. Consequently,
 294 in the case of reactive dyes used for dyeing of cellulosic fibres, wash-off is of fundamentally
 295 importance in achieving dyeings of satisfactory levels of fastness. As such, multiple wash-off baths
 296 and specific wash-off auxiliaries (aka wash-off agents) are utilised in exhaust reactive dyeing
 297 processes, as exemplified by the five-stage procedure shown in Table 8.

298

299 Table 8 recommended wash-off procedure for *Novacron FN* dyes on 100% cellulosic fibres (18)

wash-off stage	treatment*
----------------	------------

1 st	rinse: 10 mins @ 50°C
2 nd	neutralise: 10 mins @ 50°C (with CH ₃ COOH)
3 rd	soap: 15 mins @ 95°C; 0.5-2 gl ⁻¹ <i>Eriopon R liq</i> or 1-2 gl ⁻¹ <i>Albatex DS</i>
4 th	rinse: 10 mins @ 50°C
5 th	rinse: 10 mins cold

300

301

* for very deep shades an additional rinse at 90°C is recommended

302

303 The wash-off processes that are employed in the application of reactive dyes to cellulosic fibres
 304 contribute markedly to the effluent load generated in dyeing not only because of the presence of
 305 unfixed dye in the wastewater but also because of the presence of the proprietary wash-off agent
 306 that is employed. An additional contribution to the effluent load generated in reactive dyeing
 307 processes stems from the routine use of very large amounts of inorganic electrolyte (eg upto 100 gl⁻¹
 308 ¹ NaCl) to promote dye uptake onto cellulosic fibres.

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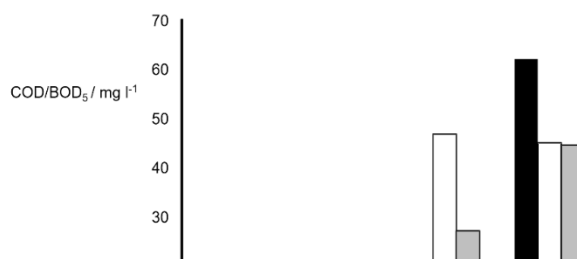
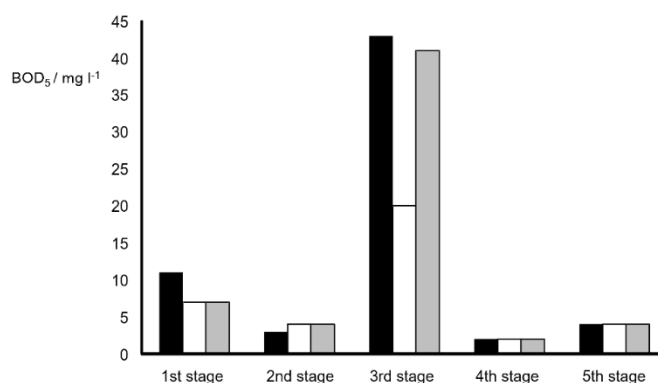
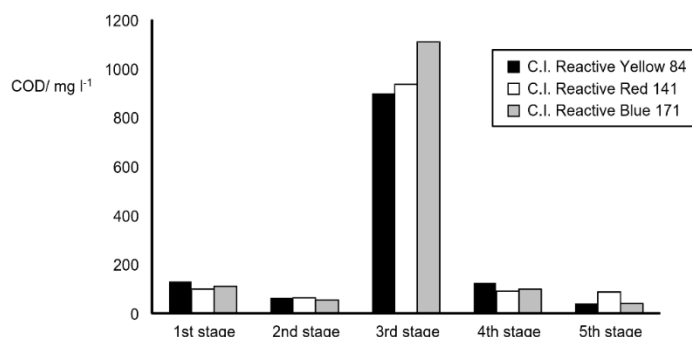
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329 Figure 3 Environmental indicators obtained for the five-stage, wash-off of 2% omf dyeings of three
330 bis(aminochlorotriazine) dyes on cotton (27)

331

332 This was demonstrated in a study that determined the COD and BOD₅ loads obtained for the wash-
333 off of three bis(aminochlorotriazine) (27) and three bifunctional (28) reactive dyes on cotton. By way
334 of example, Figure 3 shows the values of the COD, BOD₅ and COD/BOD₅ environmental indicators
335 secured for a five-stage, commercially-recommended wash-off process employed for 2% omf
336 dyeings of three bis(aminochlorotriazine) dyes (27). It is apparent that the magnitude of the COD
337 values followed the order: 1st wash-off stage > 2nd wash-off stage <<< 3rd wash-off stage >> 4th
338 wash-off stage >> 5th wash-off stage, for each of the three dyes used. It is widely acknowledged that
339 the first stage in the wash-off of reactive dyeings is important as it removes more 'easily detached'
340 unfixed reactive dye molecules and also reduces the often very high inorganic electrolyte
341 concentration within the dyed substrate, the latter function being important in terms of the complete
342 of unfixed reactive dyes. Thus, the COD obtained for the first stage of the wash-off process can be
343 attributed to the presence of 'easily detached' unfixed reactive dye molecules. Further dye removal
344 occurred during the 2nd wash-off stage, but lower amounts of unfixed dye were removed than during
345 the 1st wash-off stage. The electrolyte level in the dyed fibre would be further reduced during the 2nd
346 wash-off stage, which would aid removal of additional unfixed reactive dye during subsequent wash-
347 off stages. The finding that the highest COD values were recorded for the 3rd wash-off stage, in
348 which the proprietary wash-off auxiliary, *Sera Sperse C-SN* was used, can be attributed to both the
349 effectiveness of the wash-off auxiliary in expediting unfixed dye removal as well as the presence of
350 the auxiliary in the residual wash-off bath. In this context, it is considered (47) that ~70% of the COD

351 load generated by reactive dyeing can result from the presence of such wash-off auxiliaries. The
352 observation that the COD values obtained for the residual liquor from the 4th wash-off stage were
353 higher than those obtained for the final (5th) wash-off stage can also be ascribed to the presence of
354 the wash-off auxiliary. The values of the BOD₅ environmental indicator obtained for the five different
355 wash-off stages (Figure 3) followed the general order: 1st wash-off stage > 2nd wash-off stage <<<
356 3rd wash-off stage >> 4th wash-off stage < 5th wash-off stage, for each of the three dyes used, which
357 was very similar to that obtained for the COD values. The very high BOD₅ values obtained for the 3rd
358 wash-off stage can be assumed to reflect both high dye removal and the presence of the
359 commercial wash-off auxiliary. It is apparent that the values of COD were much higher than the
360 corresponding BOD₅ values, for each of the five wash-off stages used, indicating that whilst the
361 wash-off liquors contain organic material that can be oxidised, it is not biodegradable.

362

363 The COD/BOD₅ ratio is an indicator of the relative biodegradability of wastewater, an inverse
364 relationship existing between the ratio and biodegradability. A ratio of between 3 and 7 implies
365 moderate biodegradability whereas values >10 denote biologically untreatable wastewater and
366 indicate that additional treatment of the organic components may be required to achieve a
367 'biodegradable' COD/BOD₅ value of <3 (48). The COD/BOD₅ ratio obtained for the five wash-off
368 stages (Figure 3) clearly demonstrate the influence of the wash-off auxiliary agent upon the quality
369 of the wastewater generated for each of the three dyes, as shown by the very high ratios presented
370 by both the 3rd and, especially, the 4th wash-off stages; the very high COD/BOD₅ ratios secured for
371 the 3rd and 4th wash-off stages can be attributed to the presence of the auxiliary wash-off agent.
372 Indeed, from Figure 3 it is evident that the wastewater obtained from the majority of the wash-off
373 stages was of very low biodegradability, as the COD/BOD₅ ratios were >10.

374

375 The chemical composition of wastewater will vary according to the dyeing system under
376 consideration, type of dye used, machine employed, etc. By way of example, the typical composition
377 of the wastewater COD load for cotton yarn dyed mainly using vat dyes was 16% dyes and 46%
378 dyeing auxiliaries, whereas the corresponding figures for dyes and dyeing auxiliaries obtained in the

379 case of dyeing PA and PA/elastane blend fabrics was 2% and 54%, respectively (15). An estimate
 380 of the chemical composition of wastewater from a textile finishing mill that processed mainly
 381 synthetic fibres, (Table 9) revealed varying amounts of relatively simple inorganic compounds as
 382 well as more complex organic auxiliary materials (10).

383

384

Table 9 Chemical composition of wastewater from a textile finishing mill (10)

substance	estimated amount of the substance in wastewater/ kg yr ⁻¹
Na ₂ SO ₄	10540
CH ₃ COOH	10206
fatty alcohol ethoxylate	7512
naphthalene sulfonic acid condensation product	7070
NaOH	6344
fatty acid ethoxylate	6180
Na ₂ CO ₃	6173
butylbenzoate	4680
NaCl	4641
polyacrylate	3879
H ₂ O ₂	2093

385

386 ** the reaction of reducing agents and oxidising agents, lyes and acids in the wastewater is not considered in the estimation*

387

388 The wide range of different types of auxiliary that are likely to be present in the wastewater
 389 generated during dyeing can be anticipated to contribute to the overall environmental load; Table 10
 390 shows possible pollutants and pollution loads from dyeing (49).

391

392

Table 10 Possible pollutants and pollution loads from dyeing (49)

fibre	pH	BOD/mg l ⁻¹	total suspended solids (TSS) /mg	inorganic substances	organic substances
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l⁻¹

PES	-	480-27000	-	Na ⁺ ; NH ₄ ⁻ ; Cl ⁻ ; S ₄ O ₆ ²⁻ ; NO ₃ ⁻ ; ClO ⁻ ; SO ₃ ²⁻	acetate; anionic surfactants; antistatic agents; dispersing agents; carriers; EDTA; ethylene oxide condensates; formate; mineral oils; nonionic surfactants; residual dye; soaps; solvents
PA	8.4	368	641	Na ⁺ ; Cl ⁻ ; CO ₃ ²⁻	acetate; formate; residual dye; sulfonated oils
cotton;				Na ⁺ ; Cr ³⁺ ; Cu ²⁺ ; Sb ³⁺ ; K ⁺ ; NH ₄ ⁺ ; Cl ⁻ ; O ₃ ²⁻ ;	naphthols; acetate; amides of naphthoic acid; anionic dispersing agents; anionic surfactants; cationic fixing agents; chloro amines;
linen;	5-10	11-1800	500-14100	CO ₄ ²⁻ ; F ⁻ ; NO ₂ ⁻ ; O ₂ ²⁻ ;	formaldehyde; formate; nitro
CV				S ²⁻ ; ₂ O ₃ ²⁻ ; SO ₃ ²⁻ ;	amines; nonionic surfactants; residual dye;
				SO ₄ ²⁻	soaps; soluble oils; sulfated oils; tannic acid; tartrate; urea
PAN	1.5-3.7	175-2000	833-1968	Na ⁺ ; NH ₄ ⁻ ; Cu ²⁺ ;	acetate; aromatic amines; formate; levelling agents; phenolic compounds; residual dye;
				SO ₄ ²⁻	retardants; surfactants; thiourea dioxide
wool	4.8-8	380-2200	3855-8315	Na ⁺ ; Cr ³⁺ ; Cu ²⁺ ; Sb ³⁺ ;	acetate; dispersing agents; formate; lactate;
				K ⁺ ; NH ₄ ⁺ ; Al ³⁺ ; Cl ⁻ ;	residual dye; sulfated oils; tartrate
				CO ₃ ²⁻ ; S ₂ O ₄ ⁻ ; SO ₃ ²⁻ ;	
				SO ₄ ²⁻	

393

394 As might be anticipated, the contribution that auxiliaries make to the environmental load of
 395 wastewater will vary according to the dye-fibre system in question. For example, the contribution of
 396 dispersing agents and levelling agents is significant in the case of dyeing with vat or disperse dyes;
 397 processes such as reduction clearing and softening are also associated with high values of COD
 398 (8).

399

400

Table 11 Environmental indicators obtained for mills mainly processing a particular type of fibre (15)

fibre type	COD/ mg O ₂ l ⁻¹	BOD ₅ / mg O ₂ l ⁻¹	COD/BOD ₅
wool PA and/or CV ¹	692	240	2.9
cotton ¹	709	207	3.4
PES ²	1240	230	5.4

average of data obtained for: ¹five mills; ²three mills; ³four mills

Table 11 shows environmental indicators obtained for the dyeing and other wet processing of different types of fibre (15). The higher value of COD recorded for PES can be attributed to the dispersing agents and levelling agents used in dyeing with disperse dyes. As mentioned, the COD/BOD₅ ratio can be considered as an indicator of the relative biodegradability of wastewater (27), insofar as an inverse relationship exists between the ratio and biodegradability; the comparatively lower biodegradability of the wastewater generated from PES processing is apparent (Table 11).

4 economic aspects associated with the use of dyeing auxiliaries

From the above discussion, it is clear that the widespread use of auxiliaries in immersion dyeing will make a major contribution to the cost of dyeing not only directly, via the cost of the dyeing auxiliaries themselves, but also indirectly, because of the expense of treating the wastewater that contains auxiliaries. By way of example, as mentioned, the immersion dyeing of cotton and other cellulosic fibres requires the use of electrolyte, commonly in the form of either NaCl or Na₂SO₄, which is added to the dyebath to promote dye uptake. The amount of added electrolyte employed varies according to the particular type of dye used (eg reactive dyes, direct dyes, etc.), the nature of the fibre, liquor ratio employed, etc. For example, direct dyes are applied in the presence of typically 5-20 gl⁻¹ electrolyte whilst the dyeing of cotton with reactive dyes typically requires larger amounts of electrolyte, as high as 100 gl⁻¹ in the case of dark shades (50) and leuco dyeing with vat dyes can utilise 10-20 gl⁻¹ electrolyte depending on dyeing method. Such routine usage of high amounts of NaCl or Na₂SO₄ in cellulosic fibre dyeing poses severe environmental concerns, owing to the

425 presence of inorganic electrolyte in wastewater, as well as significant economic challenges. In the
426 latter context, the electrolyte used in cotton dyeing increases the expense of dyeing not only
427 because of the cost of the added NaCl or Na₂SO₄ but also due to the sizeable costs involved in
428 removing inorganic electrolyte from the dyed material at the end of dyeing via the use of lengthy
429 wash-off procedures and the treatment and disposal of the ensuing, already chemically-loaded,
430 saline wastewater. An idea of the scale of such treatment is provided by the water consumption
431 figures presented in Table 4 for the processing of 200 kg of cotton using typical commercial reactive
432 dyes.

433

434 In recent years, the treatment of wastewater generated from dyeing processes has received
435 considerable attention and, as mentioned, a wide range of different types of wastewater treatment
436 methods have been examined [eg (25, 35, 51-57)]. In this context, the discharge of large volumes of
437 wastewater of *high total dissolved solids (TDS)* (ie electrolyte content) generated by cotton
438 immersion dyeing processes are subject to stringent environmental restrictions in many parts of the
439 world and the use of wastewater treatments that remove electrolyte for reclamation/disposal and
440 enable recycling of some process water are nowadays unexceptional. The problems that arise from
441 the presence of inorganic electrolyte in surface water cannot be underestimated and are illustrated
442 by the well-publicised difficulties that have attended the dyeing industry centred around Tirupur
443 which prompted the local government to demand the implementation of *zero liquid discharge* [ZLD]
444 dyeing operations owing to the severe environmental impact of the use of inorganic electrolyte in
445 cellulosic fibre dyeing [eg (58-63)]. By way of example, it was reported (63) in 2008 that the daily
446 processing of 600–700 T of hosiery fabric required 400–500 T of inorganic electrolyte (either NaCl
447 or Na₂SO₄) and that TDS and chloride contents of the treated effluent were in the range 5000–7000
448 mg l⁻¹ and 2000–3500 mg l⁻¹, respectively, as compared to tolerance limits of 2100 mg l⁻¹ for TDS
449 and 1000 mg l⁻¹ for chlorides. However, such ZLD treatment systems are, typically, complex,
450 expensive and entail high running costs. By way of example, in 2015 (62) the establishment costs of
451 installing a typical ZLD system to service an installed fabric dyeing capacity of 12 T day⁻¹ was

452 €1,165,000 whilst the cost of treating the ensuing wastewater was €21.06 per m³ (Table 12) of
 453 which >95% related to TDS (electrolyte).

454 Table 12 typical costs of wastewater treatment (62)

stage of treatment	cost/€ m ⁻³
effluent treatment	0.54
reverse osmosis	0.27
multiple effect evaporator	6.75
agitator thin film dryer	13.5
total treatment cost	21.06

455

456

457 **5 the relationship between liquor ratio and the use of auxiliaries**

458 As recounted above, immersion dyeing consumes large amounts of water, as do the other wet
 459 processes to which textile fibres are subjected during their conversion into a dyed textile material,
 460 although water consumption varies markedly among such processes, as illustrated by the data
 461 shown in Table 13.

462

463 Table 13 Average water usage for different textile wet processes (49)

fibre	process	water usage/ l kg ⁻¹
cotton	desizing	3-9
	scouring	26-43
	bleaching	3-124
	mercerising	232-308
	dyeing	8-300
wool	scouring	46-100
	dyeing	16-22
	washing	334-835
polyamide	neutralisation	104-131
	bleaching	3-22
	scouring	50-67

	dyeing	17-33
	scouring	50-67
acrylic	dyeing	17-33
	final scour	67-93
	scouring	25-42
polyester	dyeing	17-33
	final scour	17-33
viscose	scouring & dyeing	17-33
	salt bath	4-13
cellulose acetate	scouring & dyeing	33-50

464

465 The amount of water used in dyeing is commonly expressed by the *liquor ratio* (aka *goods:liquor*
466 *ratio*) which simply describes the ratio of the amount of substrate used in relation to the amount of
467 water used. For example, a liquor ratio of 1:8 describes a dyeing process in which 1 kg or 1 T of
468 fibre is dyed using 8 kg (~8 l) or 8T (8000 l) of dye solution. Higher liquor ratios favour dye migration
469 during dyeing (64) whilst lower values of liquor ratio increase both the rate and extent of dyeing (65-
470 74) and, in the case of reactive dyes, the extent of covalent dye fixation (66). Various factors
471 influence the particular liquor ratio used for dyeing, such as type of fibre and its physical form, dye
472 type, machine used, etc. (1).

473

474 It follows therefore, that in the case of dyeing recipes that are based on liquor ratio as opposed to
475 mass of fibre (ie omf), liquor ratio determines the amount of chemicals (dye, wetting agent,
476 electrolyte, etc.) used for dyeing. For example, consider the case of the batchwise dyeing of 250 kg
477 of cotton with reactive dyes. Table 14 shows that using a 1:8 liquor ratio would require the use of
478 ~2000 l (~2000 kg) of water whereas the use of a 1:5 liquor ratio would necessitate the use of 1250 l
479 of water. Clearly, the lower the liquor ratio then the lower the amount of water used in dyeing (and
480 other textile wet processes). Although liquor ratio is usually based on the dry mass of the textile

481 material (fabric, yarn, etc.), some dyers and machine makers (wrongly) refer to liquor ratio on the
 482 basis of wet or wetted-out material rather than on the dry mass of the textile material.

483

484 Table 14 amounts of water, electrolyte and alkali used in a typical reactive dyeing process for 250 kg of cotton

485

liquor ratio used in dyeing	amount of water used in dyeing/ l	amount of electrolyte used in dyeing/ kg	amount of alkali used in dyeing/ kg	total amount of electrolyte and alkali consumed in dyeing/ kg	reduction in electrolyte and alkali used in dyeing compared to conventional 1:8 liquo ratio process/ %
1:8	2000	100	40	140	-
1:5	1250	62.5	25	87.5	37.5

486

487 As illustrated by the data displayed in Table 14, the liquor ratio that is employed for dyeing and the
 488 amount of the auxiliaries that are used in dyeing, are linked, insofar as, the larger the liquor ratio,
 489 the greater the amount of auxiliaries required for dyeing. It follows therefore, that the amount of
 490 water consumed in dyeing, expressed via liquor ratio, is of major economic importance, not only
 491 from the viewpoint of the direct cost of the water used, but also, and more significantly, because of
 492 the fact that the amount of auxiliaries utilised and their direct cost, are directly related to the amount
 493 of water employed. Indeed, the adoption of low liquor ratios in dyeing has beneficial effects in terms
 494 of the cost of dyeing, not only from the viewpoint of auxiliary usage but also, for example, from the
 495 related perspective of the amounts of water, steam and energy consumed (75-79), as illustrated by
 496 the data shown in Table 15 (79).

497

498 Table 15 estimated cost savings of ultra low liquor ratio (1:3 for synthetic fibres and 1:5 for cotton) dyeing
 499 equipment compared to conventional (1:10 liquor ratio) equipment (79)

cost factor	change/%
water	-37.0
steam	-50.3

electricity	0
direct labour	-104
chemicals	-43.9
supplies	-1.1
overhead	-10.6

500

501 When the amount of the auxiliaries that are used in dyeing is calculated on the basis of mass of
 502 fibre, liquor ratio has a marked effect on the effective concentration of the auxiliary that is present in
 503 the dyebath, which, in turn, has implications in terms of, for example, the manner by which the
 504 auxiliary functions, the treatment required for its removal from wastewater, etc. For example,
 505 consider the use of a fibre protective agent that is deployed at 5% omf in a process for dyeing 250
 506 kg of fibre. If a 1:10 liquor ratio is used for dyeing, the auxiliary would have a concentration in the
 507 dyebath of 5 gl⁻¹ whereas at a 1:6 liquor ratio, the concentration of the fibre protective agent would
 508 be 8 gl⁻¹. It is common for dye makers to prescribe the amount of auxiliaries (and dye) required
 509 depending on the particular ratio selected for dyeing (Table 16) (18).

510

511 Table 16 amounts of added electrolyte and alkali required for immersion dyeing using *Novacron FN* dyes (18)

liquor ratio	electrolyte & alkali	dye/% omf						
		< 0.5	0.5	1	2	3	4	≥5
≤ 1:6	NaCl/ gl ⁻¹	10	20	30	40	50	60	70
	NaHCO ₃ / gl ⁻¹	14	16	18	20	20	20	20
1:6 < LR ≤ 1:8	NaCl/ gl ⁻¹	20	30	40	50	60	70	80
	NaHCO ₃ / gl ⁻¹	10	12	14	16	18	20	20
> 1:8	NaCl/ gl ⁻¹	30	40	50	60	80	90	100
	NaHCO ₃ / gl ⁻¹	8	10	12	14	16	18	18
≤ 1:6	NaCl/ gl ⁻¹	10	20	30	40	50	60	70
	NaHCO ₃ / gl ⁻¹	10	10	5	50	5	5	5
	NaOH 36°Bé/ cm ³ l ⁻¹	0.5	1	2	2.5	3	3.5	4
1:6 < LR ≤ 1:8	NaCl/ gl ⁻¹	20	30	40	50	60	70	80
	NaHCO ₃ / gl ⁻¹	10	5	5	5	5	5	5

	NaOH 36°Bé/ cm ³ l ⁻¹	-	0.75	1.25	1.5	2	2.5	3
	NaCl/ gl ⁻¹	30	40	50	60	80	90	100
> 1:8	NaHCO ₃ / gl ⁻¹	8	5	5	5	5	5	5
	NaOH 36°Bé/ cm ³ l ⁻¹	-	0.5	1	1.25	1.5	2	2.5

512

513 As discussed previously, the amount of water consumed in dyeing has major environmental
 514 implications. For example, in the case of China, where shortage of water resources is severe,
 515 insofar as >300 of the 640 major cities face water shortages and 100 cities face severe scarcities
 516 (40), textile dyeing and finishing processes are characterised by high water consumption, with some
 517 150 m³ of water being consumed per tonne of cloth processed (40). Clearly, the use of lower liquor
 518 ratios in dyeing can result in lower amounts of wastewater that contain smaller amounts of
 519 auxiliaries.

520

521 6 summary

522 The many types of dyeing auxiliary that are commercially available vary, not only in terms of the
 523 nature of the assistance they furnish in immersion dyeing processes, but also from the viewpoints of
 524 their environmental credentials and the costs associated with their use. Despite their widespread
 525 usage, the precise nature of the mode of action of many auxiliaries has not been fully resolved.

526

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ACCEPTED MANUSCRIPT

Highlights

- there are many different types of dyeing auxiliary
- they are chemically diverse and perform many essential operations
- the precise mode of action of many auxiliaries is unclear