JOURNAL OF FUTURE
Journal homepage: future-journal.uz

Original Research Article
Volume 2, Issue 5, 2026

Publisher: Uranium Publishing LLC

TEKSTIL MATERIALLARINI BO‘YASH JARAYONLARI UCHUN MOYLOVCHI KOMPOZITSIYANI D-OPTIMAL BLENDING ASOSIDA ISHLAB CHIQISH: 5×5 TARKIB–XOSSA MODELI VA EKSPERIMENTAL VALIDATSIYA

Davletov Zafar Quvondiq o‘g‘li*

Tashkent Institute of Chemical Technology
ORCID: 0009-0001-0416-6302

* Corresponding author: zdavletov297@gmail.com

ARTICLE INFO

Dates:
Received: 14.08.2026
Revised: 25.08.2026
Accepted: 28.08.2026

DOI:
10.66960/jof.3093-8899.00038

ANNOTATSIYA

TMPTO, PEG-400 dioleat, etoksillangan kastor moyi (ECO), sulfatlangan kastor moyi (SCO) va natriy poliakrilatdan iborat APEO-free tekstil bo‘yash moyining 20 ta cheklangan D-optimal formulasi eksperimental tekshirildi. Birlamchi javoblar sifatida 40 °C dagi kinematik qovushqoqlik (ν40), sirt tarangligi (γ), 7 kunlik emulsiya barqarorligi (ES), tola-tola (μff) va tola-metall (μfm) ishqalanish koeffitsientlari olindi. 20 tajribaga moslashtirilgan to‘liq ikkinchi tartibli Scheffé modellari barcha javoblar uchun statistik ahamiyatli bo‘ldi (R^2=0.9863–0.9986; p≤0.00104). B-20 (38.2/28.1/17.1/10.5/6.1 mass.%) uchun ν40=21.5 mm²/s, γ=33.2 mN/m, ES=93.5%, μff=0.21 va μfm=0.17, umumiy desirability D=0.854 bo‘ldi. Kolloid validatsiyada D50=185 nm, PDI=0.24 va ζ=-32.0 mV qayd etilib, 500 mg/L CaCO3 qattiqligidagi suvda to‘liq barqarorlik kuzatildi. Oqartirilgan va merserizatsiyalangan 100% paxta matosini (145 g/m²) Reactive Blue 19 bilan n=3 bo‘yashda B-20 K/S=15.65±0.15, bo‘yoq yutilishi=93.50±0.26% va CV(K/S)=0.88±0.06% natijalarni berdi; blankda mos ravishda 11.25±0.18, 68.30±0.56% va 3.10±0.11%, tijorat analogida 14.82±0.13, 88.17±0.40% va 1.45±0.07% olindi. Bir omilli ANOVA va Tukey HSD asosiy koloristik ko‘rsatkichlar bo‘yicha guruhlar orasida statistik ahamiyatli farqlarni ko‘rsatdi (p<0.01). Natijalar B-20 ni kolloid barqarorlik, boshqariladigan ishqalanish va bo‘yash sifati bo‘yicha muvozanatlangan formula sifatida asoslaydi.

Kalit so’zlar: tekstil bo‘yash moyi, D-optimal blending, Scheffé modeli, desirability, tribologiya, Reactive Blue 19, K/S.

АННОТАЦИЯ

Экспериментально исследованы 20 ограниченных D-оптимальных составов APEO-free смазочно-противозаломной композиции на основе TMPTO, диолеата PEG-400, этоксилированного касторового масла, сульфатированного касторового масла и полиакрилата натрия. Определяли кинематическую вязкость при 40 °C (ν40), поверхностное натяжение (γ), 7-суточную устойчивость эмульсии (ES), коэффициенты трения волокно-волокно (μff) и волокно-металл (μfm). Полные квадратичные модели Шеффе для 20 опытов были значимы для всех откликов (R^2=0.9863–0.9986; p≤0.00104). Для B-20 (38.2/28.1/17.1/10.5/6.1 мас.%) получены ν40=21.5 мм²/с, γ=33.2 мН/м, ES=93.5%, μff=0.21, μfm=0.17 и общая desirability D=0.854. Коллоидная валидация дала D50=185 нм, PDI=0.24 и ζ=-32.0 мВ при полной устойчивости в воде с 500 мг/л CaCO3. При трехкратном крашении отбеленной и мерсеризованной хлопчатобумажной ткани (145 г/м²) Reactive Blue 19 состав B-20 обеспечил K/S=15.65±0.15, exhaustion=93.50±0.26% и CV(K/S)=0.88±0.06%; для контроля значения составили 11.25±0.18, 68.30±0.56% и 3.10±0.11%, а для коммерческого аналога 14.82±0.13, 88.17±0.40% и 1.45±0.07%. Однофакторный ANOVA с Tukey HSD подтвердил значимые различия между группами (p<0.01). Состав B-20 характеризуется сбалансированным сочетанием коллоидной устойчивости, трибологических свойств и эффективности крашения.

Ключевые слова: текстильное крашение, смазка красильной ванны, D-оптимальный план смесей, модель Шеффе, desirability, трибология, Reactive Blue 19.

ABSTRACT

Twenty constrained D-optimal blends of an APEO-free dyebath lubricant/anti-crease composition containing trimethylolpropane trioleate (TMPTO), PEG-400 dioleate, ethoxylated castor oil (ECO), sulfated castor oil (SCO) and sodium polyacrylate were experimentally screened. The primary responses were kinematic viscosity at 40 °C (ν40), surface tension (γ), 7-day emulsion stability (ES), fiber-fiber friction (μff) and fiber-metal friction (μfm). Full second-order Scheffé models fitted to the 20-run design were significant for all responses (R^2=0.9863–0.9986; p≤0.00104). B-20 (38.2/28.1/17.1/10.5/6.1 mass.%) gave ν40=21.5 mm²/s, γ=33.2 mN/m, ES=93.5%, μff=0.21 and μfm=0.17; multi-response desirability was D=0.854. Colloidal validation gave D50=185 nm, PDI=0.24 and ζ=-32.0 mV, with complete stability in water containing 500 mg/L CaCO3. In triplicate dyeing of bleached and mercerized 100% cotton (145 g/m²) with Reactive Blue 19, B-20 produced K/S=15.65±0.15, dye exhaustion=93.50±0.26% and CV(K/S)=0.88±0.06%, compared with 11.25±0.18, 68.30±0.56% and 3.10±0.11% for the blank and 14.82±0.13, 88.17±0.40% and 1.45±0.07% for a commercial lubricant. One-way ANOVA followed by Tukey HSD showed significant differences among the three groups (p<0.01 for the principal colorimetric responses). The results identify B-20 as a balanced formulation combining colloidal stability, controlled friction and improved dyeing performance.

Keywords: textile dyeing, dyebath lubricant, D-optimal mixture design, Scheffé model, desirability, tribology, Reactive Blue 19, K/S.

How to cite:
Davletov Z.Q. (2026). **TEKSTIL MATERIALLARINI BO‘YASH JARAYONLARI UCHUN MOYLOVCHI KOMPOZITSIYANI D-OPTIMAL BLENDING ASOSIDA ISHLAB CHIQISH: 5×5 TARKIB–XOSSA MODELI VA EKSPERIMENTAL VALIDATSIYA**. *Journal of Future*, 2(5), 14-19. https://doi.org/10.66960/jof.3093-8899.00038

1. Kirish

Tekstil materiallarini jet, soft-flow va boshqa nam ishlov berish apparatlarida bo‘yashda mato qatlamlari o‘zaro va metall yo‘naltiruvchi qismlar bilan takroriy kontaktda bo‘ladi. Bunday mexanik ta’sir crease/rope mark, chafing va lokal rang notekisligini kuchaytiradi. Shu sababli bo‘yash vannasiga qo‘shiladigan moylovchi/anti-crease kompozitsiya ishqalanishni kamaytirishi, lekin bo‘yoqning tolaga yutilishi va rang intensivligiga salbiy ta’sir ko‘rsatmasligi kerak [1–4].

Formulatsiyaning amaliy samaradorligi faqat qovushqoqlik bilan belgilanmaydi: suvda dispersiyalanish, emulsiya barqarorligi, sirt xossalari, ko‘piklanish, qattiq suvga chidamlilik, tola–tola va tola–metall tribologiyasi hamda K/S, ΔE, bo‘yoq yutilishi va rang tekisligi birgalikda baholanishi lozim. Mazkur ishda shu javoblar bosqichli eksperimental dasturga birlashtirildi.

Komponent ulushlari yig‘indisi 100% ga teng bo‘lganligi sababli formulatsiya oddiy 5×5 factorial tizim sifatida emas, mixture design sifatida qaraldi. Tadqiqotning maqsadi TMPTO, PEG-400 dioleat, ECO, SCO va natriy poliakrilat asosidagi 20 ta D-optimal blendni eksperimental screeningdan o‘tkazish, Scheffé modeli bilan tarkib–xossa bog‘lanishini baholash va eng muvozanatlangan formulani 100% paxta–Reactive Blue 19 tizimida real bo‘yash orqali validatsiya qilishdan iborat.

2. Materiallar va usullar

2.1. Formulatsiya komponentlari

Faol paket APEO-free yondashuvda tanlandi. Alkilfenol etoksilatlar o‘rniga nonionik kastor-moyi etoksilatlari va PEG esterlaridan foydalanildi [8]. Besh asosiy komponent faol modda bazasida 100% ga normallashtirildi. Bo‘yash validatsiyasida Reactive Blue 19 (C.I. 61200, tozalik ≥95%, Sigma-Aldrich) va oqartirilgan, merserizatsiyalangan plain-weave 100% paxta matosi (145 g/m²) ishlatildi.

2.2. Mixture design va matematik model

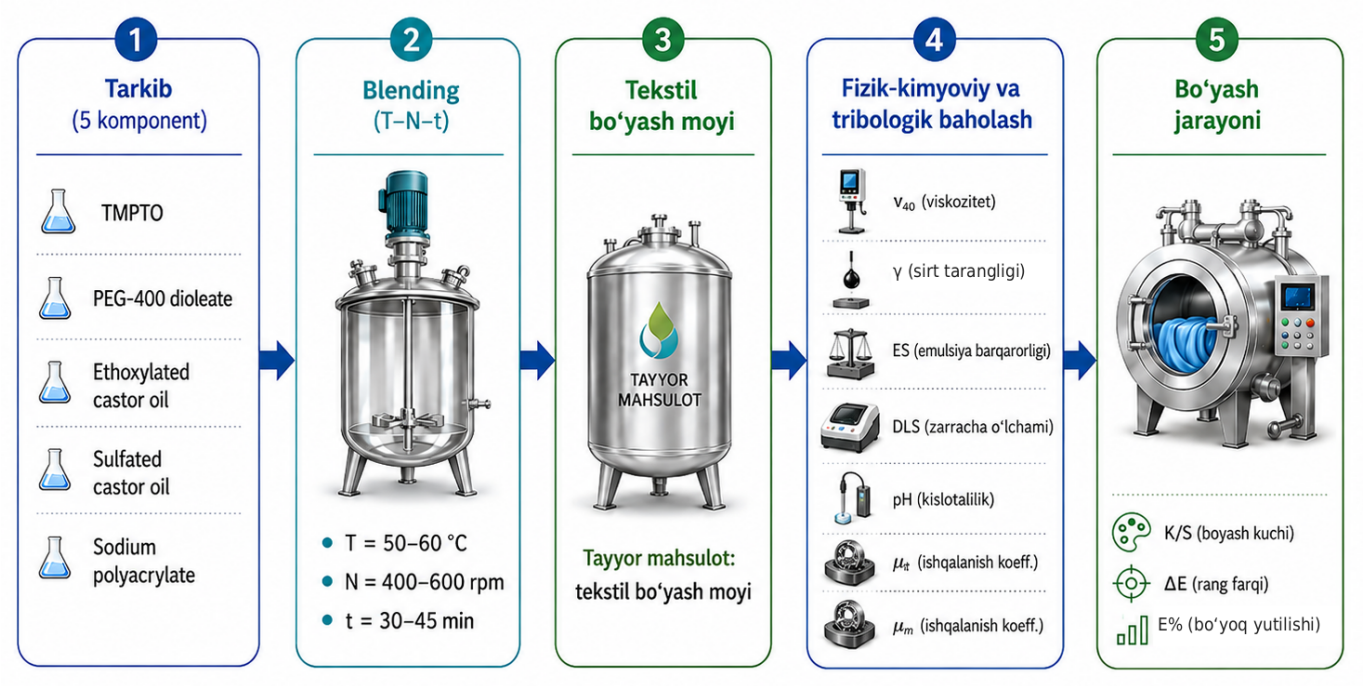
Besh komponentli tizim uchun asosiy cheklov quyidagicha qabul qilindi:

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1,\ x_i \geq 0. \quad (1)$$

Har bir javob funksiyasi uchun ikkinchi tartibli Scheffé modeli qo‘llanadi:

$$\hat{Y} = \Sigma\beta_i x_i + \Sigma\beta_{ij} x_i x_j. \quad (2)$$

Bunda chiziqli hadlar komponentlarning individual hissasini, $x_i x_j$ hadlari esa juft komponentlarning o‘zaro ta’sirini ifodalaydi. Ushbu



1-rasm. Tekstil bo‘yash moyini ishlab chiqish va qo‘llashning besh bosqichli tadqiqot sxemasi.

1-jadval. Blending uchun tanlangan besh komponent va ularning funksional roli.

Kod	Komponent	Asosiy vazifa	Chegara, mass.%
X_1	Trimethylolpropane trioleate (TMPTO)	Asosiy ester moylovchi; adsorbsion tribologik qatlam	30–50
X_2	PEG-400 dioleate	Gidrofil ester; moylash + emulsiyalanish	20–35
X_3	Ethoxylated castor oil (ECO)	Nonionik emulsifikator; namlash va suvli muhitga moslik	10–25
X_4	Sulfated castor oil (SCO)	Anion ko-emulsifikator; elektrolit muhitida dispersiya	5–15
X_5	Sodium polyacrylate	Polimer anti-crease/dispersant; himoya qatlam	2–10

ishda T, N va t alohida optimallashtirish omillari emas, boshqariladigan blending sharoitlari sifatida saqlandi; matematik model faqat kompozitsion D-optimal mixture design javoblariga qurildi.

20 nuqtali cheklangan D-optimal mixture design qo‘llandi; har bir blend faol paket bo‘yicha 100 g miqdorda tayyorlandi. Kvadratik Scheffé modelida 5 ta chiziqli va 10 ta juft o‘zaro ta’sir hadi mavjud. To‘liq koeffitsientlar 20 ta tajriba natijasidan eng kichik kvadratlar usuli bilan qayta baholandi. Model adekvatligi R^2, tuzatilgan R^2, RMSE, F-mezon va p-qiymat bilan tekshirildi; cheklangan dizayn sababli koeffitsientlar faqat tadqiqot sohasi ichidagi lokal prediktiv model sifatida talqin qilindi [5–7].

2.3. Blending tartibi va jarayon omillari

Komponentlar gravimetrik dozalanib, TMPTO va PEG-400 dioleat ester bazasini, ECO va SCO emulgirlovchi/sirt-faol qismini, natriy poliakrilat esa polimer anti-crease/dispersant qismini tashkil etdi. Blending 50–60 °C, 400–600 rpm va 30–45 min boshqariladigan texnologik oynada olib borildi. Screeningdan keyin B-04, B-08, B-09, B-12 va B-20 kolloid sinovga, B-20 esa qattiq suv va real bo‘yash validatsiyasiga o‘tkazildi.

2.4. Tahlil usullari

v_{40} va zichlik Anton Paar SVM 3001 Stabinger viskozimetrida ISO 23581:2024/ASTM D7042 asosida, sirt tarangligi Krüss K100 tensiometrida Wilhelmy plate usulida o‘lchandi [9,10]. 5% li emulsiyaning 7 kunlik barqarorligi 25 °C da ES=(1−Vsep/Vtotal)×100% orqali baholandi. D50, PDI va ζ-potensial Malvern Zetasizer Nano ZS da DLS/ELS usulida; μff va μfm UMT/CETR tribometrida reciprocating rejimda μ=Ff/Fn bo‘yicha aniqlandi. Rang o‘lchovlari Datacolor 800 spektrofotometrida D65 yoritgich va 10° kuzatuvchi bilan bajarildi. K/S Kubelka-Munk tenglamasi orqali, bo‘yoq yutilishi E=[(A0−A1)/A0]×100% va CV(K/S)=s/x̄×100% bo‘yicha hisoblandi. ΔE*ab qiymatlari ISO/CIE 11664-4:2019 ga muvofiq CIELAB Euclidean masofasi sifatida blankning o‘rtacha L*a*b* koordinatalariga nisbatan qayta hisoblandi [11]. Bo‘yash natijalari n=3 uchun mean±SD ko‘rinishida berildi; guruhlar bir omilli ANOVA va Tukey HSD (α=0.05) bilan solishtirildi.

2.5. Reproduktiv bo‘yash retsepti

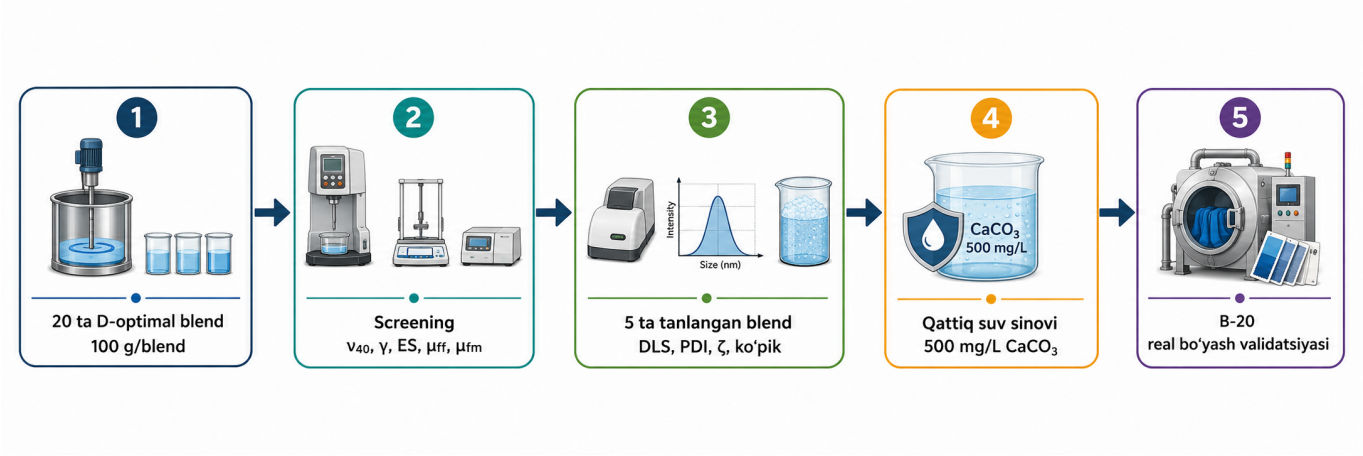
Har bir bo‘yash tajribasida 10.0 g mato, liquor ratio 1:10 va Reactive Blue 19 2.0% owf qo‘llandi. Moy dozasi Blank uchun 0 g/L, Commercial va B-20 uchun 3.0 g/L edi. Vannaga Na_2SO_4 40 g/L va Na_2CO_3 15 g/L kiritildi, pH 10.8–11.2 da ushlab turildi. Harorat 2 °C/min tezlikda 60 °C gacha ko‘tarilib, 60 min izotermik ushlab turildi. Keyin 10 min sovuq chayish, 60 °C da 10 min issiq yuvish, 2 g/L noionik surfaktant bilan 95 °C da 15 min soaping va yakuniy sovuq chayish-quritish bajarildi.

3. Natijalar va muhokama

20 ta blend bo‘yicha o‘lchangan natijalar formulatsiyada aniq fizik-kimyoviy va tribologik kompromiss mavjudligini ko‘rsatdi. Shu sababli optimal formula bitta javob ekstremumi bo‘yicha emas, D-optimal mix-

2-jadval. Besh komponentli cheklangan D-optimal mixture design (active basis).

№	X_1 TMPTO	X_2 PEG-dio.	X_3 ECO	X_4 SCO	X_5 Polyacr.
1	38.7	21.1	24.8	5.7	9.7
2	44.1	34.4	10.4	8.0	3.1
3	48.6	20.4	20.9	8.1	2.0
4	30.4	25.6	24.5	9.7	9.8
5	50.0	27.6	15.3	5.1	2.0
6	49.2	20.4	13.5	14.7	2.2
7	31.2	34.1	17.4	14.9	2.3
8	36.7	35.0	14.0	5.0	9.4
9	38.0	20.7	17.1	14.3	10.0
10	40.8	27.8	23.9	5.2	2.2
11	36.0	21.0	24.8	14.7	3.5
12	31.4	20.2	23.9	15.0	9.6
13	40.4	29.3	10.1	14.7	5.5
14	48.2	26.3	11.1	5.0	9.4
15	30.3	34.8	23.8	5.4	5.6
16	31.1	34.0	23.6	9.1	2.1
17	49.9	20.6	17.2	5.8	6.6
18	30.3	34.6	10.6	14.5	10.0
19	48.1	20.1	10.0	12.3	9.5
20	**38.2**	**28.1**	**17.1**	**10.5**	**6.1**



2-rasm. Tekstil bo'yash moyi kompozitsiyalarini bosqichma-bosqich eksperimental tanlash va B-20 formulasini validatsiya qilish sxemasi

3-jadval. Eksperimental tahlillar, asboblar va javob funksiyalari.

Blok	Ko'rsatkich	Asbob/metod	Natija
Fizik-kimyoviy	ν_{40}, ρ, pH, γ	Anton Paar SVM 3001; Krüss K100	mm^2/s; g/cm^3; pH; mN/m
Kolloid	ES, D50, PDI, ζ, ko'pik, qattiq suv	Malvern Zetasizer Nano ZS; 7 kunlik ES	%; nm; –; mV; mL
Tribologiya	μff, μfm	UMT/CETR tribometer, reciprocating	o'lchovsiz
Kolorimetriya	K/S, L*a*b*, ΔE*ab, E%, CV(K/S)	Datacolor 800; D65/10°	–; %
Statistika	Scheffé; ANOVA; Tukey HSD	Least squares; α=0.05	R^2; F; p-value

ture modeli, Derringer-Suich desirability, kolloid barqarorlik va real bo'yash validatsiyasi birgalikda hisobga olinib tanlandi.

3.1. Screening natijalari va Scheffé modelining adekvatligi

Screeningda ν_{40} 18.0–28.0 mm^2/s, γ 31.5–36.0 mN/m, ES 85.0–96.0%, μff 0.17–0.26 va μfm 0.14–0.21 oralig'ida o'zgardi. 20 ta real tajribadan qayta baholangan to'liq kvadratik Scheffé modeli ν_{40} uchun R^2=0.9986 (R^2adj=0.9948; RMSE=0.265; F=260.33; p=3.44×10^{-6}), γ uchun R^2=0.9971 (R^2adj=0.9888; RMSE=0.170; F=120.92; p=2.32×10^{-5}), ES uchun R^2=0.9984 (R^2adj=0.9939; RMSE=0.306; F=220.35; p=5.21×10^{-6}), μff uchun R^2=0.9920 (R^2adj=0.9695; RMSE=0.00534; F=44.10; p=2.79×10^{-4}) va μfm uchun R^2=0.9863 (R^2adj=0.9479; RMSE=0.00524; F=25.68; p=0.00104) berdi. Barcha modellar statistik ahamiyatli bo'ldi; to'liq β-koeffitsientlar 4-jadvalda keltirilgan.

Javoblar orasidagi Pearson korrelyatsiyasi tarkibning ko'p mezonli tabiatini tasdiqladi: r(ν_{40},γ)=0.995, r(ν_{40},ES)=–0.955, r(ν_{40},μff)=–0.973, r(γ,μff)=–0.980, r(ES,μff)=0.904 va r(μff,μfm)=0.989. Demak, ishqalanishni keskin kamaytiruvchi kom-

pozitsiyalar ko‘pincha emulsiya barqarorligini pasaytirish tendensiyasiga ega bo‘lgan.

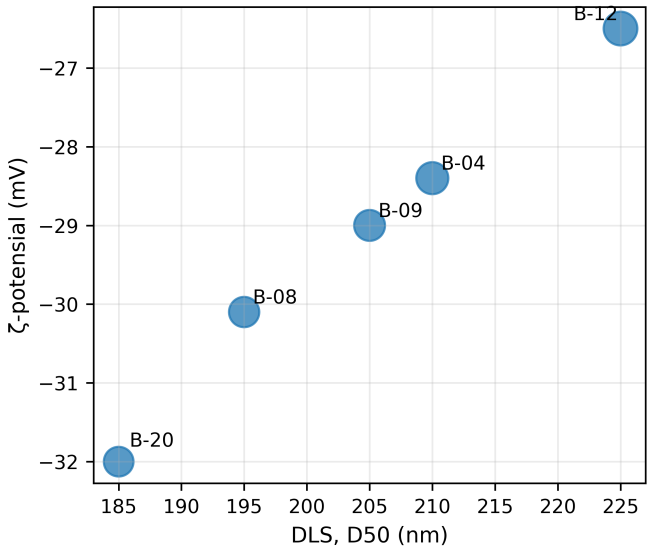
Masalan, B-05 va B-17 eng past μff/μfm qiymatlaridan birini (0.17/0.14) bergan bo‘lsa-da, ularning ES qiymati mos ravishda 85.0 va 85.5% bo‘ldi. Aksincha, B-12 da ES=96.0% bo‘lib, μff=0.25 va μfm=0.21 qayd etildi. Bu qarama-qarshilik yakuniy formulani faqat tribologiya yoki faqat emulsiya barqarorligi bo‘yicha tanlash ilmiy jihatdan yetarli emasligini ko‘rsatadi.

3.2. Ko‘p mezonli tanlash va B-20 formulasi

Screeningdan B-04, B-08, B-09, B-12 va B-20 chuqurlashtirilgan tahlilga ajratildi. B-20 faol paket tarkibi TMPTO/PEG-400 dioleat/ECO/SCO/natriy poliakrilat = 38.2/28.1/17.1/10.5/6.1 mass.% bo‘lib, ν_{40}=21.5 mm^2/s, γ=33.2 mN/m, ES=93.5%, μff=0.21 va μfm=0.17 natijalarni berdi. Derringer-Suich ko‘p javobli funksiyasi bo‘yicha D_B-20=0.854 bo‘ldi (dv=0.920, dγ=0.960, dES=0.935, dμff=0.760, dμfm=0.720). To‘liq qayta moslashtirilgan Scheffé modeli B-20 uchun mos ravishda 21.54 mm^2/s, 33.33 mN/m, 93.40%, 0.205 va 0.165 ni bashorat qildi; eksperimental nisbiy og‘ishlar 0.10–2.79% diapazonda bo‘ldi. Bu B-20 ning tanlanishini nafaqat screening, balki model validatsiyasi bilan ham asoslaydi.

3.3. Kolloid va qattiq suv barqarorligi

Tanlangan besh blend orasida B-20 eng kichik DLS o‘lchamini (D50=185 nm), eng past PDI qiymatini (0.24) va eng manfiy ζ-potensialni (−32.0 mV) ko‘rsatdi. Ko‘pik hajmi 10 mL bo‘lib, 500 mg/L $CaCO_3$ qattiqligidagi suvda faza ajralishi yoki cho‘kma kuzatilmadi. B-20 emulsiyasining zichligi ρ=0.908 g/cm^3, 10% li emulsiyaning pH qiymati 6.95±0.10 (20 °C) bo‘ldi. Taqqoslash uchun B-12 da D50=225 nm, PDI=0.31 va ζ=−26.5 mV qayd etildi. Kolloid natijalar B-20 ni real bo‘yash sinoviga olib chiqishni asoslaydi.



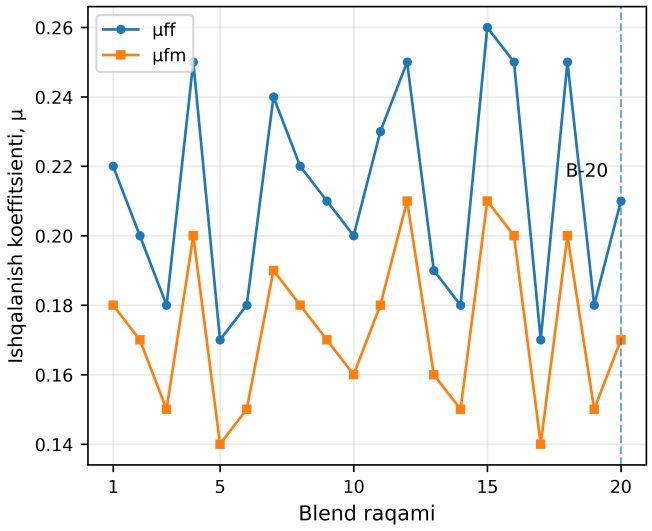
3-rasm. Tanlangan besh blendning kolloid xaritasi: DLS zarracha o‘lchami va ζ-potensial o‘rtasidagi bog‘lanish; marker o‘lchami PDI ga proporsional.

3.4. Tribologik javoblar

20 ta formula bo‘yicha μff 0.17–0.26, μfm esa 0.14–0.21 oralig‘ida bo‘ldi. μff va μfm o‘rtasidagi juda yuqori korrelyatsiya (r=0.989) ikkala kontakt turiga formulatsiya tarkibi bir yo‘nalishda ta’sir qilishini ko‘rsatadi. B-20 uchun μff=0.21 va μfm=0.17 bo‘lib, u mutlaq minimumni bermagan; biroq ES=93.5%, keyingi DLS/PDI/ζ ko‘rsatkichlari va qattiq suvdagi to‘liq barqarorlik bilan birga qaralganda eng muvozanatlangan amaliy profil hosil qilgan.

3.5. Real bo‘yash va statistik validatsiya

Yakuniy sinovlar oqartirilgan va merserizatsiyalangan 100% paxta matosi (145 g/m^2)–Reactive Blue 19 tizimida Blank, Commercial va B-20 guruhlarida n=3 takror bilan bajarildi. Blankda moylovchi kompozitsiya ishlatilmadi; Commercial va B-20 guruhlarida 3.0 g/L moy qo‘llandi. K/S, L*a*b*, E% va CV(K/S) bir xil bo‘yash rejimida solishtirildi. ΔE*ab blank o‘rtacha koordinatalariga nisbatan L*a*b* qiymatlaridan qayta hisoblandi.



4-rasm. 20 ta D-optimal blend uchun tola–tola (μff) va tola–metall (μfm) ishqalanish koeffitsientlari; B-20 keyingi validatsiya formulasi sifatida ko‘rsatilgan.

B-20 uchun K/S=15.65±0.15 bo‘lib, blankka (11.25±0.18) nisbatan 39.1% va commercial analogga (14.82±0.13) nisbatan 5.6% yuqori bo‘ldi. Bo‘yoq yutilishi B-20 da 93.50±0.26%, commercialda 88.17±0.40% va blankda 68.30±0.56% bo‘ldi. Rang notekisligi CV(K/S) B-20 da 0.88±0.06% gacha kamayib, blankka nisbatan 71.6% va commercialga nisbatan 39.3% pasaydi. Bir omilli ANOVA K/S ($F=694.07$, $p=7.97\times10^{-8}$), L* ($F=709.99$, $p=7.45\times10^{-8}$), a* ($F=333.24$, $p=7.10\times10^{-7}$), b* ($F=440.08$, $p=3.10\times10^{-7}$), E% ($F=2921.33$, $p=1.08\times10^{-9}$) va CV(K/S) ($F=572.43$, $p=1.42\times10^{-7}$) bo‘yicha guruhlar orasida sezilarli farq borligini ko‘rsatdi; Tukey HSD da har uch guruh bir-biridan $p<0.05$ darajada farq qildi. Blankga nisbatan qayta hisoblangan ΔE*ab commercial uchun 7.29±0.38, B-20 uchun 9.24±0.35 bo‘ldi. Bu kattaroq ΔE B-20 ning blankdan kuchliroq rang o‘zgarishini ko‘rsatadi; u rang mosligi maqsadi bo‘lmaganligi sababli desirability mezoniga kiritilmadi.

*Izoh: bir ustundagi turli ustki harflar Tukey HSD bo‘yicha $p<0.05$ farqni bildiradi. ΔE*ab blankning o‘rtacha L*a*b* koordinatalariga nisbatan qayta hisoblangan va uch guruhli ANOVA ga kiritilmagan.*

Statistik izoh. Bo‘yash guruhlarida n=3 individual takrorlar asosida mean±SD, bir omilli ANOVA va Tukey HSD hisoblandi. Bayonnomadagi ΔE ustuni L*a*b* koordinatalari va ΔE*ab formulasi bilan to‘liq mos kelmagani sababli maqolada ΔE*ab qiymatlari blankning o‘rtacha koordinatalariga nisbatan qayta hisoblandi. Model koeffitsientlari esa 20 ta D-optimal tarkib va ularning real screening javoblaridan to‘liq 15 hadli Scheffé modeli sifatida qayta baholandi.

4. Xulosa

1. Besh komponentli APEO-free tekstil bo‘yash moyi uchun 20 nuqtali cheklangan D-optimal mixture design real eksperimental javoblar bilan muvaffaqiyatli modellashtirildi; to‘liq kvadratik Scheffé modellari R^2=0.9863–0.9986 va $p\leq0.00104$ darajasida ahamiyatli bo‘ldi.

2. Screening moylovchanlik va emulsiya barqarorligi o‘rtasida aniq kompromissni ko‘rsatdi; shu sababli yakuniy formula ko‘p mezonli desirability va keyingi kolloid/bo‘yash validatsiyasi bilan tanlandi.

3. B-20 (TMPTO/PEG-400 dioleat/ECO/SCO/natriy poliakrilat = 38.2/28.1/17.1/10.5/6.1 mass.%) uchun D=0.854 bo‘lib, D50=185 nm, PDI=0.24, ζ=−32.0 mV, ρ=0.908 g/cm^3 va pH=6.95±0.10 qayd etildi; 500 mg/L $CaCO_3$ qattiqligidagi suvda to‘liq barqarorlik saqlandi.

4-jadval. 20 ta cheklangan D-optimal tajriba bo‘yicha qayta baholangan to‘liq Scheffé β-koeffitsientlari va model statistikasi (x_i — 0–1 mass fraksiyalar).

Koeff.	ν_{40}	γ	ES	μff	μfm
β1	68.367	49.419	-31.566	0.39319	0.37414
β2	-28.069	1.518	118.939	1.29668	1.27986
β3	58.880	30.686	-9.650	1.35756	1.29485
β4	133.468	62.856	-74.780	-0.14020	-0.07511
β5	-30.220	20.013	205.201	1.54590	0.55467
β12	18.753	32.961	171.590	-2.21027	-2.12233
β13	-121.486	-28.936	377.893	-2.00279	-1.98155
β14	-207.073	-59.924	484.295	0.17823	0.14713
β15	14.986	-6.213	100.478	-2.00157	-0.99711
β23	5.543	47.093	28.644	-2.66162	-2.92770
β24	-26.866	15.109	-8.987	-0.91981	-1.33109
β25	100.397	48.737	-228.059	-2.33525	-1.76476
β34	-272.307	-70.270	374.906	0.29592	-0.06204
β35	-23.334	-2.455	49.117	-1.88334	-0.30027
β45	-173.443	-62.506	-45.556	-0.69144	0.70163
R^2	0.9986	0.9971	0.9984	0.9920	0.9863
R^2adj	0.9948	0.9888	0.9939	0.9695	0.9479
RMSE	0.265	0.170	0.306	0.00534	0.00524
F	260.33	120.92	220.35	44.10	25.68
p	3.44e-06	2.32e-05	5.21e-06	2.79e-04	1.04e-03

5-jadval. 20 ta D-optimal blend uchun eksperimental screening natijalari.

Blend	ν_{40}, mm²/s	γ, mN/m	ES, %	μff	μfm
B-01	22.4	33.1	94.0	0.22	0.18
B-02	24.1	34.5	89.5	0.20	0.17
B-03	26.8	35.2	87.0	0.18	0.15
B-04	18.2	31.8	95.5	0.25	0.20
B-05	28.0	36.0	85.0	0.17	0.14
B-06	27.5	35.8	86.2	0.18	0.15
B-07	19.0	32.1	93.8	0.24	0.19
B-08	20.5	32.9	95.0	0.22	0.18
B-09	21.0	33.0	94.2	0.21	0.17
B-10	23.2	34.0	91.0	0.20	0.16
B-11	20.8	32.7	94.5	0.23	0.18
B-12	18.5	31.6	96.0	0.25	0.21
B-13	23.9	34.2	90.5	0.19	0.16
B-14	27.1	35.5	86.0	0.18	0.15
B-15	18.0	31.5	95.0	0.26	0.21
B-16	18.7	31.9	94.8	0.25	0.20
B-17	27.8	35.9	85.5	0.17	0.14
B-18	18.3	31.7	93.0	0.25	0.20
B-19	26.9	35.4	86.8	0.18	0.15
B-20	**21.5**	**33.2**	**93.5**	**0.21**	**0.17**

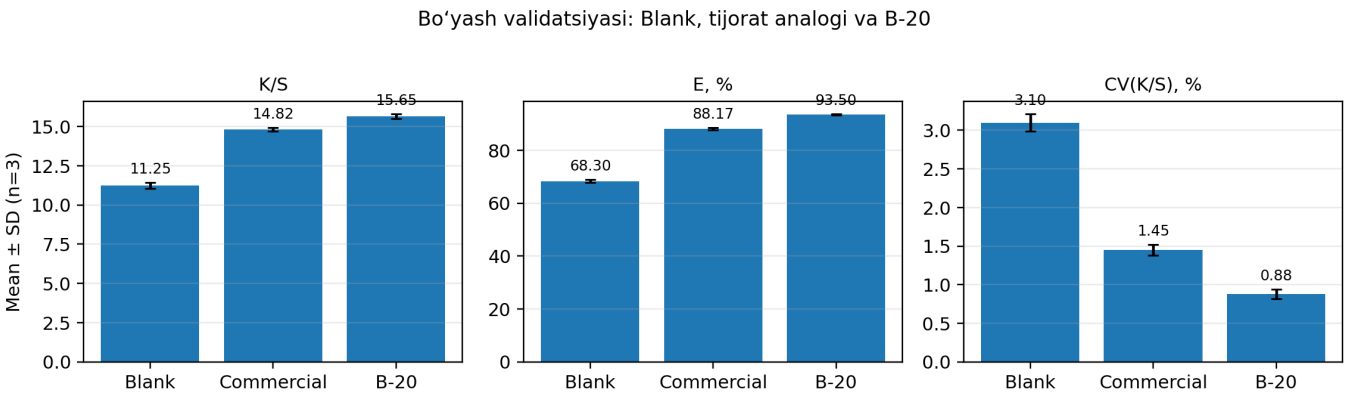
6-jadval. n=3 bo‘yash validatsiyasi: mean±SD va bir omilli ANOVA natijalari.

Guruh	K/S	L*	a*	b*	E, %	CV(K/S), %	ΔE*ab vs Blank
Blank	11.25 ± 0.18^{a}	38.08 ± 0.23^{a}	-2.11 ± 0.07^{a}	-22.38 ± 0.23^{a}	68.30 ± 0.56^{a}	3.10 ± 0.11^{a}	0 (ref.)
Commercial	14.82 ± 0.13^{b}	32.38 ± 0.28^{b}	-1.16 ± 0.06^{b}	-26.83 ± 0.25^{b}	88.17 ± 0.40^{b}	1.45 ± 0.07^{b}	7.29±0.38
B-20	15.65 ± 0.15^{c}	31.03 ± 0.23^{c}	-0.86 ± 0.06^{c}	-28.22 ± 0.28^{c}	93.50 ± 0.26^{c}	0.88 ± 0.06^{c}	9.24±0.35
ANOVA p	7.97×10^{-8}	7.45×10^{-8}	7.10×10^{-7}	3.10×10^{-7}	1.08×10^{-9}	1.42×10^{-7}	—

4. n=3 bo‘yash validatsiyasida B-20 K/S=15.65±0.15 va E=93.50±0.26% natijalarni berdi; blankka nisbatan K/S 39.1% oshdi, CV(K/S) esa 3.10±0.11% dan 0.88±0.06% gacha kamaydi.

5. Commercial analog bilan taqqoslanganda B-20 K/S ni 5.6% va bo‘yoq yutilishini 5.33 foiz punkt oshirdi, CV(K/S) ni 39.3% kamaytirdi. ANOVA/Tukey HSD asosiy koloristik ko‘rsatkichlar bo‘yicha farqlar statistik ahamiyatli ekanini tasdiqladi ($p<0.05$).

6. Natijalar B-20 ni 100% paxta–Reactive Blue 19 tizimi uchun kolloid barqarorligi, boshqariladigan ishqalanish va rang intensivligi/tekisligi bo‘yicha muvozanatlangan dyebath lubricant/anti-crease formula sifatida asoslaydi. Xulosalar aynan ushbu substrat, bo‘yoq va tajriba chegaralariga tegishli.



5-rasm. Blank, tijorat analogi va B-20 uchun K/S, bo‘yoq yutilishi E% va CV(K/S) natijalari (mean±SD, n=3).

ADABIYOTLAR RO‘YXATI

[1] Fahmy H.M., Amr A. Synthesis of castor oil/PEG as textile softener. Scientific Reports. 2024;14:7208. https://doi.org/10.1038/s41598-024-56917-2.

[2] Ethox Chemicals. ETHOX CO-81 (PEG-80 castor oil): dyeing assistant and lubricant for textile fibers. Technical product information.

[3] Pervez M.N., Yeo W.S., Lin L., et al. Optimization and prediction of the cotton fabric dyeing process using Taguchi design-integrated machine learning approach. Scientific Reports. 2023;13:12363. https://doi.org/10.1038/s41598-023-39528-1.

[4] Boukouvalas D.T., Rosa J.M., Belan P.A., et al. Optimization of cotton dyeing with reactive dyestuff using multiobjective evolutionary algorithms. Chemometrics and Intelligent Laboratory Systems. 2021;219:104441. https://doi.org/10.1016/j.chemolab.2021.104441.

[5] Bezerra M.A., Lemos V.A., Novaes C.G., et al. Application of mixture design in analytical chemistry. Microchemical Journal. 2020;152:104336. https://doi.org/10.1016/j.microc.2019.104336.

[6] Li Z., Lu D., Gao X. Optimization of mixture proportions by statistical experimental design using response surface method – A review. Journal of Building Engineering. 2021;36:102101. https://doi.org/10.1016/j.jobe.2020.102101.

[7] Chen J., Ling L., Zhang C. D- and A-optimal designs for multiresponse mixture experiments with qualitative factors. Communications in Statistics – Theory and Methods. 2024;53(15):5593–5611. https://doi.org/10.1080/03610926.2023.2223705.

[8] ZDHC Foundation. Manufacturing Restricted Substances List (MRSL), Version 3.1. Alkylphenols and alkylphenol ethoxylates: restrictions for textile formulations.

[9] ISO 23581:2024. Petroleum products and related products — Determination of kinematic viscosity — Method by Stabinger type viscometer.

[10] ASTM D7042-25. Standard Test Method for Dynamic Viscosity and Density of Liquids by Stabinger Viscometer (and the Calculation of Kinematic Viscosity). ASTM International.

[11] ISO/CIE 11664-4:2019. Colorimetry — Part 4: CIE 1976 L*a*b* colour space.