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NARRATIVE REVIEW

E5, E10, E15, E20 up to E50 Petrol: Use, Benefits and Disadvantages, with Reaction Chemistry, Engine Corrosion and Vehicle Compatibility-A Narrative Review

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ABSTRACT

Blending **anhydrous ethanol** with petrol is the most widely deployed route for partially displacing fossil gasoline in spark-ignition vehicles. This narrative review examines ethanol–petrol blends from E5 to E50 (5–50 % ethanol by volume): Current use, physico-chemical behaviour, reaction chemistry, benefits, disadvantages, engine and fuel-system corrosion, and which vehicles tolerate which blends. India, which has moved from an average of about 5 % blending in 2019–20 to roughly 20 % by 2025–26 [1–3], is the main case study, supplemented by Brazil, where E30 became the mandatory blend in August 2025 [4], and the United States, where E15 is approved for model-year 2001 and newer light-duty vehicles [5]. Ethanol raises octane rating and oxygen content, which permits knock-resistant, more complete combustion and generally lowers tailpipe CO, hydrocarbons and particle number, but it holds only about two-thirds of the energy of petrol per litre, increases acetaldehyde emissions, and swells or degrades some elastomers and plastics [6–10]. Reaction schemes are given for combustion, acetaldehyde formation, the formation of acetic acid (by oxidation, by acetic-acid bacteria and in the crankcase) and the corrosion reactions it drives. The evidence indicates that metals are little affected by E20 in laboratory immersion tests, that the credible corrosion drivers are water, dissolved oxygen, acetic acid and chloride contamination rather than ethanol itself, and that rubber and plastic parts of vehicles built before about 2020–2023 are the main compatibility risk. Independent mileage tests show E20 penalties of about 4–13 % against government-reported figures of 1–6 %. Practical improvements in fuel quality, vehicle design and owner information are proposed, together with a checklist for owners. E10 is a low-risk baseline, E15–E20 is feasible for compatible and calibrated fleets and E30–E50 is technically promising mainly for flex-fuel or purpose-optimised engines.

Keywords: Ethanol-blended petrol; E20; gasohol; octane number; acetaldehyde; acetic acid; fuel-system corrosion; flex-fuel vehicles; vehicle compatibility; India

1. Introduction

Road transport depends overwhelmingly on liquid hydrocarbons. India's net petroleum imports were about 185 Mt in 2020–21, at a cost of roughly US$55 billion, and the expert committee that drafted the national roadmap argued that a successful E20 programme could save about US$4 billion a year [11]. Blending ethanol with petrol, using existing refuelling infrastructure and internal-combustion vehicles, is therefore attractive for energy security, farm incomes and, potentially, air quality and climate.

The shorthand E*x* denotes a fuel containing *x* % ethanol by volume; E5, E10, E15 and E20 are 5, 10, 15 and 20 % ethanol, and E50 is a half-and-half mixture. Low blends (E5–E10) are used in most conventional engines worldwide; in the United States, more than 98 % of petrol is reported to contain ethanol as an oxygenate and octane booster [6]. Intermediate blends (E15–E30) require attention to materials, calibration and labelling, and higher blends (E40–E50 and above) sit between conventional petrol and E85 flex-fuel and are mainly a research and flex-fuel-vehicle topic [8,12,13].

Public discussion in India has intensified since the E20 roll-out. Government agencies state that studies by ARAI, SIAM and Indian Oil Corporation found no engine damage and only modest mileage loss,

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while consumer groups, insurers, some manufacturers and opposition parties have questioned compatibility, fuel quality, mileage and consumer choice [14–16,54–58]. Vehicle owners are asking practical questions: Why does acetic acid form in the fuel? Do engines and fuel systems corrode? Which vehicles can use which blend, and which cannot? Can anything be improved, and what is in the owner's favour? This review brings laboratory, vehicle and policy evidence together to answer them. Its objectives are to (i) describe use and regulatory status of E5–E50, (ii) summarise fuel properties, (iii) present the reaction chemistry, including acetic-acid formation, (iv) review benefits, (v) review corrosion, materials and other disadvantages, (vi) map vehicle tolerance, and (vii) propose improvements and practical guidance for owners.

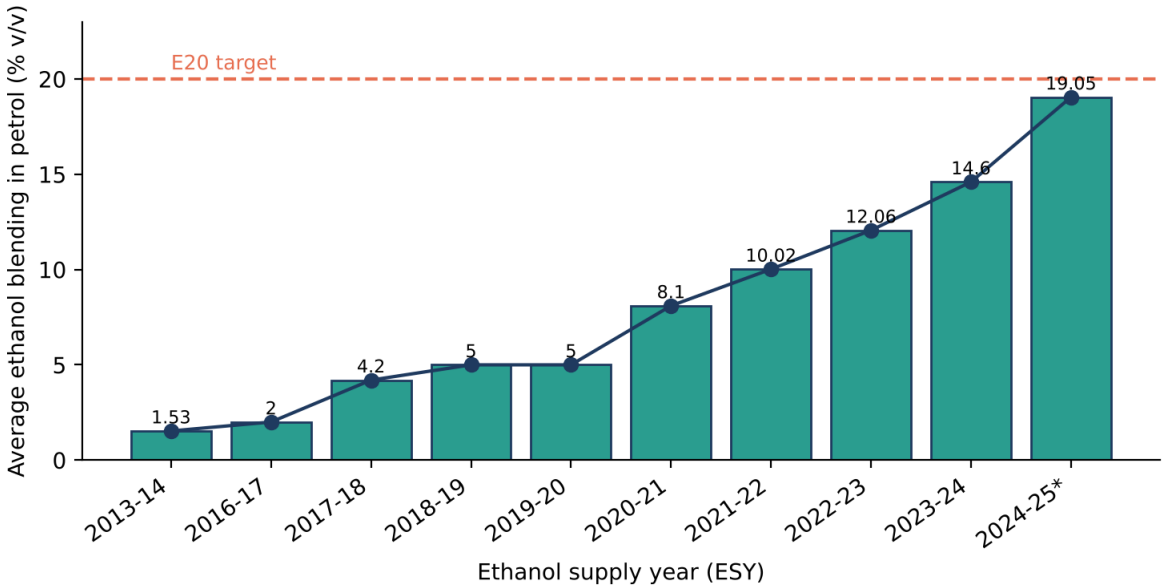
2. Methodology of the Review

This is a narrative (non-systematic) review. Peer-reviewed papers, laboratory technical reports (U.S. National Renewable Energy Laboratory, Oak Ridge National Laboratory, American Petroleum Institute), standards (Bureau of Indian Standards, ASTM as cited by API), government and intergovernmental documents (NITI Aayog, Parliament of India, U.S. Department of Energy, IEA Advanced Motor Fuels programme) and dated news reports of official statements, manufacturer statements and independent road tests were identified through web searches in November 2026 and cross-checked against the original publisher, repository or agency page where available. News reports are used only to document official and industry statements, field reports and test results, not as scientific evidence of mechanism. Where the author has calculated values (Table 3, Figures 4 and 5, and the carbon dioxide per unit energy quoted in Scheme 2), the assumptions are stated so that readers can reproduce them. The reaction schemes follow cited kinetic and corrosion studies; where a step is a general chemical expectation rather than a measured result, the text says so. The qualitative assessments (Figures 9 and 10) are the author's synthesis and are labelled as such.

3. Status and Use of E5 to E50 Blends

Table 1 summarises where each blend level is used. India's national average blending moved from 1.53 % in the early part of the programme [17] to 5.0 % in ESY 2018–19 and 2019–20, 8.1 % in 2020–21, 10.02 % in 2021–22, 12.06 % in 2022–23 and 14.6 % in 2023–24 [1,18]; the average reached 19.05 % by 31 July 2025 [2] and was reported at 19.98 % on 31 January 2026 [3] (Figure 1). The roadmap had advanced the E20 target from 2030 to 2025–26 [11]. E20 is now the standard grade sold at Indian retail outlets, with 100-octane petrol the main ethanol-free exception [57]. Figure 2 places these milestones, with U.S. and Brazilian decisions, on one timeline, and Scheme 1 outlines the supply chain from feedstock to vehicle.

Figure 1. Progress of India's ethanol-blended petrol programme

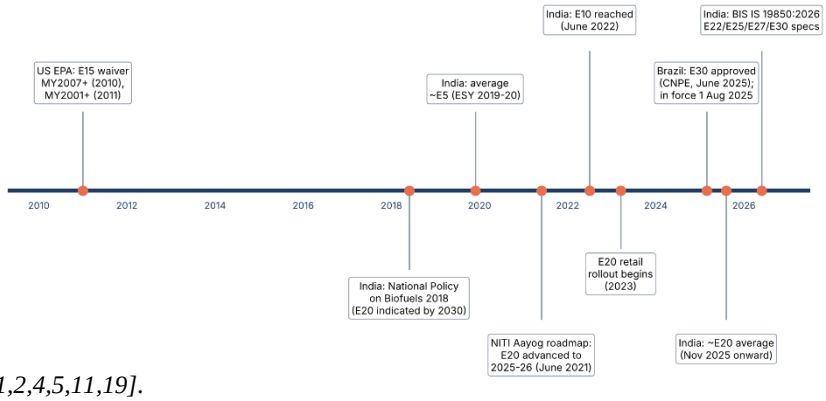


Note: ESY = ethanol supply year; the 2024–25 value (asterisked in the plot) is the cumulative average to 31 July 2025. Data: [1,2,17,18].

Table 1. Where and how E5–E50 petrol is used (selected jurisdictions)

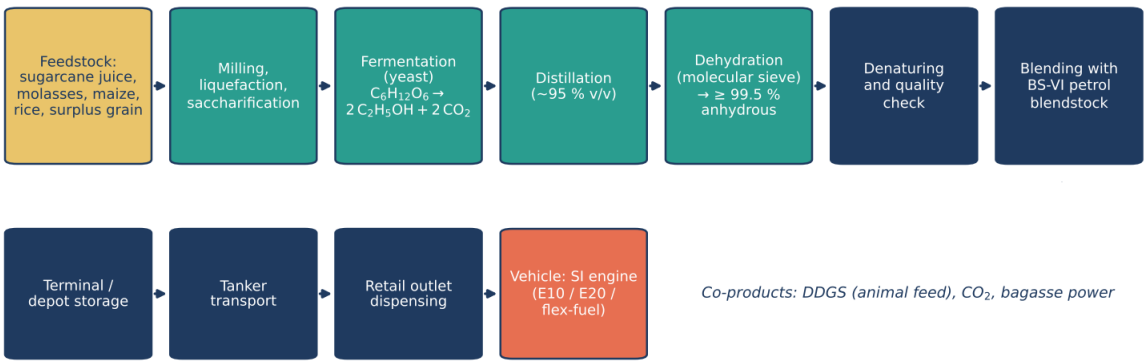
Blend	Status and use	Vehicles / constraints
E5	India's national average was about 5 % in ESY 2018–19 and 2019–20 [1]	Suitable for all petrol vehicles; minimal change to engines or fuel systems.
E10	India reached about 10 % in 2021–22 [18]; the standard blend for most U.S. petrol [6]	Compatible with the existing petrol fleet; the usual baseline for comparisons.
E15	United States: approved for light-duty conventional vehicles of model year 2001 and newer and for flex-fuel vehicles [5]	Not approved for motorcycles, heavy-duty vehicles, off-road engines or pre-2001 vehicles in the U.S. [5].
E20	India: national standard grade from 2025 [2,3,57]	E20-compatible new vehicles; some older BS-III vehicles may need earlier replacement of rubber parts and gaskets, per the government [14,15].
E22–E30	India: BIS specification IS 19850:2026 for E22, E25, E27 and E30 notified, without an immediate national roll-out mandate [19,20]. Brazil: E30 mandatory for regular petrol from 1 August 2025 (premium kept at 25 %) [4,21]	Fleet readiness, calibration and labelling needed; flex-fuel capability helps. ARAI has been asked to study E25 in E10- and E20-compatible vehicles [57]. U.S. DOE laboratory work has examined E30 in legacy flex-fuel vehicles [13].
E40–E50	No national mandate identified in this review; studied in laboratories for octane, materials and emissions [8,12,22]	Flex-fuel or purpose-optimised engines; infrastructure and materials must be qualified for high-ethanol service.

Figure 2. Timeline of selected ethanol-blend milestones



Note: dates from [1,2,4,5,11,19].

Scheme 1. Ethanol-blended petrol value chain



Fuel-grade ethanol is produced by fermentation and distillation, dehydrated, denatured, blended with petrol blendstock at terminals and dispensed at retail outlets; E10, E20 or higher-ethanol vehicles then use it. Maize is reported as the single largest feedstock (about half of supply) in ESY 2024–25 [3]. Water and chloride can enter at several points, which matters for corrosion (Section 8).

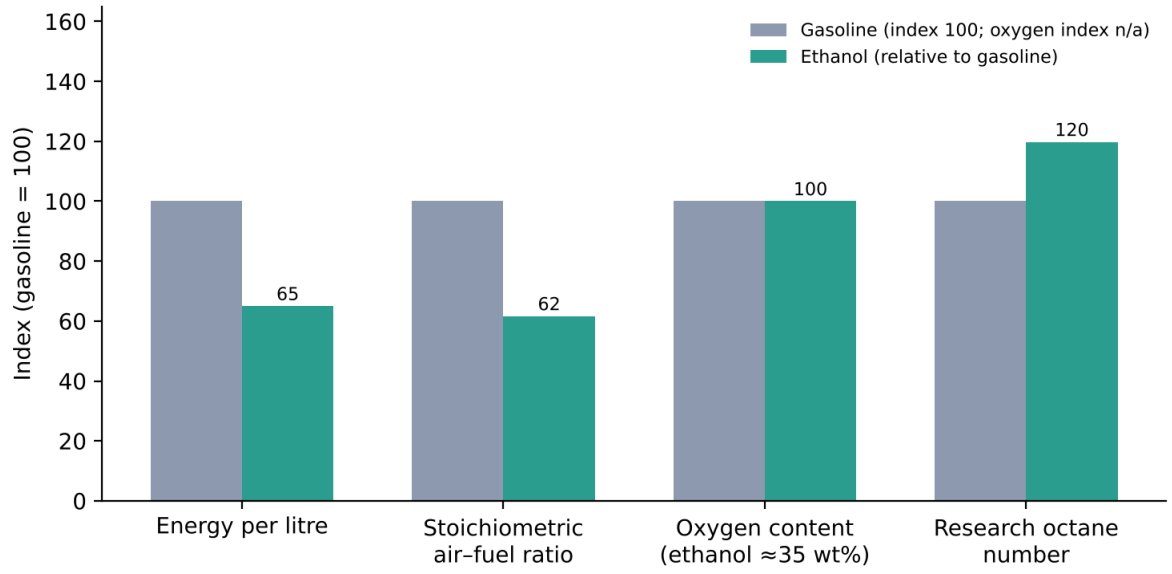
4. Physico-chemical Properties of Ethanol and Ethanol–Petrol Blends

Ethanol (C_2H_5OH) differs from petrol in four properties that drive nearly every benefit and disadvantage of blending (Table 2, Figure 3). Its volumetric energy content is only about 65 % of petrol (about 21 MJ/L) [7]; the U.S. Department of Energy states that pure ethanol contains about 34 % less energy per gallon than petrol [6]. Its density is 0.79 kg/L, its oxygen content is about 35 wt %, and its stoichiometric air–fuel ratio is 9.0 compared with 14.6 for petrol [7]. Ethanol also has a markedly higher latent heat of vaporisation than petrol, which cools the intake charge but complicates cold starts in high-ethanol fuels; the cold-start limit of neat ethanol is reported near +12 °C, and the problem is reduced by retaining at least 15 % petrol [7].

Table 2. Selected properties of petrol and ethanol

Property	Petrol (typical)	Ethanol	Source
Volumetric energy content	≈32 MJ/L	≈21 MJ/L (≈65 % of petrol)	[6,7]
Density	≈0.72–0.78 kg/L	0.79 kg/L	[7]
Stoichiometric air–fuel ratio (kg/kg)	14.6	9.0	[7]
Oxygen content	≈0 wt %	≈35 wt %	[7]
Research octane number (RON)	≈88–95 (blendstock to market grade)	≈108–109	[22,23]
Latent heat of vaporisation	Lower	Higher (cooling effect)	[7]
Water tolerance	Very low	Fully miscible; blends tolerate more water as ethanol rises	[7]

Figure 3. Key properties of ethanol relative to gasoline

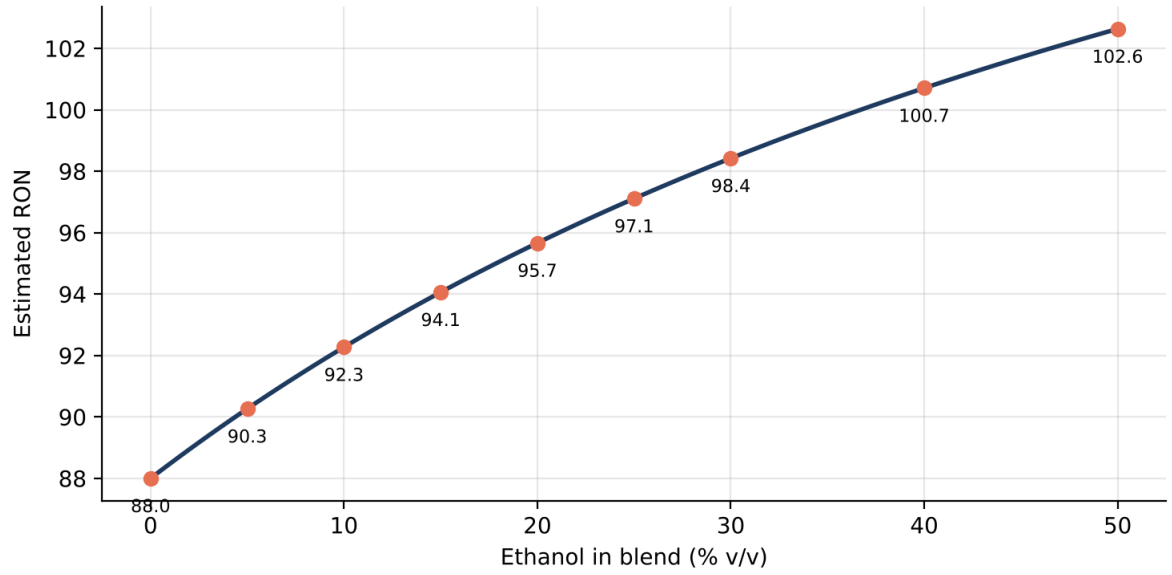


Note: indices computed from the values in Table 2; the oxygen bar indicates ethanol's ≈35 wt % oxygen against essentially none in petrol.

4.1 Octane response

Because octane numbers blend almost linearly on a molar rather than volumetric basis, small additions of ethanol appear to give disproportionately large octane gains when expressed per volume [23]. Measurements of E0–E75 blends in blendstocks of 82–95 RON confirmed that a molar blending model, plus a small second-order term, describes the data to within about one octane number [22]. Using the linear molar model, an 88-RON blendstock would reach roughly 92 RON at E10, 96 RON at E20 and 99 RON at E30 (Table 3, Figure 4); real blends tend to be slightly higher because of synergy [22,24]. An independent Indian test measured 98.2 RON for regular E20 and 98.8 RON for the premium 95-octane grade [57], above the calculated value because the commercial blendstock is not the 88-RON stock assumed in the model. Such octane gains allow more advanced spark timing or higher compression ratios and are the main technical argument for mid- and high-level blends [25,26].

Figure 4. Estimated RON of ethanol–gasoline blends (88 RON blendstock)



Note: calculated by the author using the linear molar model [23] with assumed densities (ethanol 0.789, petrol 0.745 kg/L), molar masses (46.07 and 100 g/mol) and RON values (ethanol 109; blendstock 88). Illustrative only.

4.2 Energy content and fuel economy

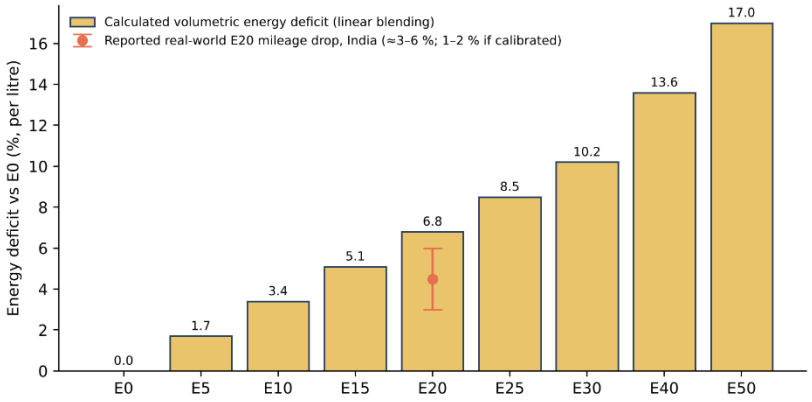
If energy per litre blended linearly, each 10 percentage points of ethanol would reduce volumetric energy by about 3.4 % (Table 3, Figure 5); moving from E10 to E20 would therefore cost about 3.5 % (93.2 against 96.6). Observed fuel-economy penalties differ by vehicle: engines optimised for petrol typically lose mileage roughly in proportion to energy content, whereas octane-enabled efficiency gains can offset part of the loss in appropriately calibrated engines [6,25]. In a seven-vehicle fleet (1984–2007) tested on E10, E20, E50 and E85, fuel economy fell with increasing ethanol content in later-model vehicles [8]. For India, the Ministry of Petroleum and Natural Gas has stated a mileage reduction of about 1–2 % for E10-built vehicles calibrated for E20 and 3–6 % for other vehicles [14], and the road transport minister told Parliament in July 2026 that E20 may reduce fuel efficiency by 2–6 % depending on vehicle category and age [15]. Independent controlled tests tell a less uniform story (Figure 6): four cars lost 3.8–12.6 % on E20 relative to E10, the largest losses occurring in a 2024 car and a 2016 BS-IV car, so there is no single figure for every vehicle [57]. Real-world, independently audited fleet data remain a key research gap [16].

Table 3. Calculated properties of ethanol–petrol blends (author's calculation)

Blend	Ethanol mole fraction	Estimated RON	Oxygen (wt %)	Stoich. AFR	Energy vs E0 (%)
E0	0.000	88.0	0.0	14.6	100.0
E5	0.108	90.3	1.8	14.1	98.3
E10	0.203	92.3	3.7	13.7	96.6
E15	0.289	94.1	5.5	13.3	94.9
E20	0.365	95.7	7.3	12.9	93.2
E25	0.434	97.1	9.1	12.6	91.5
E30	0.496	98.4	10.8	12.2	89.8
E40	0.605	100.7	14.4	11.6	86.4
E50	0.697	102.6	17.8	11.1	83.0

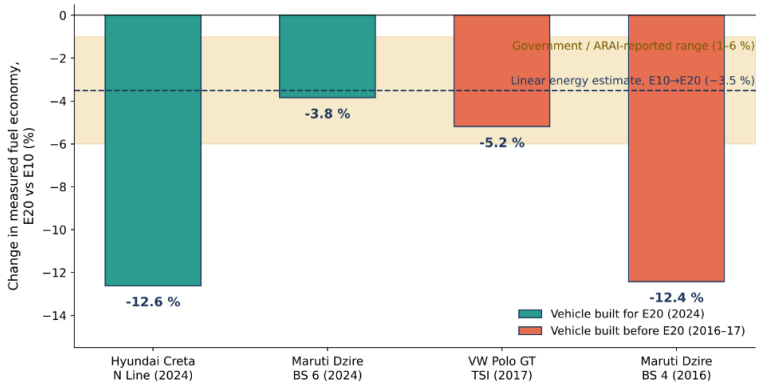
Assumptions: linear molar octane model [23]; ethanol density 0.789 kg/L, petrol 0.745 kg/L, molar masses 46.07 and 100 g/mol; RON 109 (ethanol) and 88 (blendstock); stoichiometric air–fuel ratios 9.0 and 14.6 [7]; oxygen 34.7 wt % in ethanol; energy deficit 34 % per unit ethanol [6]. Values are estimates, not measurements.

Figure 5. Volumetric energy deficit of ethanol blends



Note: the red marker shows the 3–6 % real-world range reported by Indian authorities for E20 [14,15]; 1–2 % applies to vehicles calibrated for E20. The linear calculation is close to the lower end of independent tests (Figure 6) and above government figures for calibrated vehicles.

Figure 6. Independent E20 versus E10 mileage tests in four cars



Note: measured by Autocar India under identical conditions on E20 and E10 (Creta N Line 10.59 vs 12.12 km/L; Dzire BS 6 14.24 vs 14.81; Polo GT TSI 9.13 vs 9.63; Dzire BS 4 9.80 vs 11.19) [57]. The shaded band is the government/ARAI-reported 1–6 % range [14,57]; the dashed line is the linear energy estimate from Table 3. Four vehicles cannot represent the fleet; the figure shows spread, not an average.

5. Reaction Chemistry of Ethanol-blended Petrol

The practical questions asked by vehicle owners (why aldehydes appear, why acetic acid is mentioned in fuel specifications, why some parts corrode) all trace back to a small set of reactions. They are collected here as numbered steps, R1 to R24, so that later sections can refer to them.

5.1 Combustion and the role of bound oxygen

Complete combustion of ethanol (R1, Scheme 2) releases about 1367 kJ per mole of liquid ethanol, while iso-octane, used here as a surrogate for petrol, releases about 5461 kJ per mole (R2). Because ethanol carries its own oxygen, it needs only 9.0 kg of air per kg against about 15 for iso-octane, which is why an engine must inject proportionally more ethanol-blend, and why older carburetted or open-loop engines, whose mixture does not adapt, run effectively leaner on blends [7]. Incomplete combustion (R3) is suppressed as the oxygen content rises, in line with the lower CO and hydrocarbons recorded in vehicle tests [8,29]. Per unit of fuel energy the tailpipe CO_2 is almost the same for the two fuels (about 71 against 70 g/MJ on a lower-heating-value basis, using 26.8 and 44.3 MJ/kg), so any climate benefit depends on the biogenic origin of the carbon and on life-cycle accounting (Section 10), not on the tailpipe.

Scheme 2. Combustion, acetaldehyde formation and atmospheric fate of ethanol-blended petrol (reactions R1–R10)

(a) Net combustion reactions of ethanol and petrol (iso-octane as surrogate)

R1 $C_2H_5OH + 3\,O_2 \rightarrow 2\,CO_2 + 3\,H_2O$

complete combustion; $\Delta cH^\circ \approx -1367$ kJ mol^{-1} (liquid ethanol); the bound oxygen (≈35 wt %) leans the mixture

R2 $C_8H_{18} + 12.5\,O_2 \rightarrow 8\,CO_2 + 9\,H_2O$

iso-octane; $\Delta cH^\circ \approx -5461$ kJ mol^{-1}; stoichiometric air–fuel ratio ≈15 for iso-octane against 9.0 for ethanol (by mass)

R3 $C_2H_5OH + 2\,O_2 \rightarrow 2\,CO + 3\,H_2O$

incomplete combustion (rich or cold-wall regions); CO and hydrocarbons fall as ethanol content rises [8,29]

Tailpipe CO_2 per unit of fuel energy is nearly equal: ≈71 g MJ^{-1} (ethanol) vs ≈70 g MJ^{-1} (iso-octane), lower-heating-value basis (author's calculation); any climate benefit comes from biogenic carbon, not the tailpipe.

(b) Acetaldehyde: why the unregulated-emission penalty rises with ethanol content

R4 $C_2H_5OH + OH^\bullet \rightarrow CH_3C^\bullet HOH + H_2O$

hydrogen abstraction, mainly at the α-carbon; β-carbon and O–H abstraction are minor channels [50,51]

R5 $CH_3C^\bullet HOH + O_2 \rightarrow CH_3CHO + HO_2^\bullet$

low-barrier step that makes acetaldehyde the characteristic partial-oxidation product of ethanol [50]

R6 $CH_3CHO + OH^\bullet \rightarrow CH_3C^\bullet O + H_2O \rightarrow CH_3^\bullet + CO \rightarrow CO_2$

further oxidation in the flame; acetaldehyde survives mainly in quenched or unburned zones

R7 $CH_3CHO + 2.5\,O_2 \rightarrow 2\,CO_2 + 2\,H_2O$

over the warm three-way catalyst, which removes most acetaldehyde; cold starts are the weak point

(c) Atmospheric fate of exhaust acetaldehyde: peroxyacetyl nitrate (PAN)

R8 $CH_3CHO + OH^\bullet \rightarrow CH_3C^\bullet O + H_2O$

R9 $CH_3C^\bullet O + O_2\,(+M) \rightarrow CH_3C(O)OO^\bullet$

acetylperoxy radical

R10 $CH_3C(O)OO^\bullet + NO_2 \rightleftharpoons CH_3C(O)OONO_2$ (PAN)

PAN is an eye irritant and a reservoir of NO_2; modelling of E85 found higher PAN and, regionally, more ozone [52]

Reading: blends cut CO, hydrocarbons and BTEX but add aldehydes; the net air-quality effect depends on catalyst performance, fleet age and local chemistry, and is smaller for E10–E20 than for E85 modelled in [52].

Note: R1–R3 net combustion reactions; R4–R7 radical route to acetaldehyde and its removal [50,51]; R8–R10 atmospheric chemistry leading to PAN [52]. ΔcH° values are standard thermochemical data. CO_2 per MJ is the author's calculation.

5.2 Acetaldehyde: The characteristic by-product

Acetaldehyde is the most consistent unregulated-emission penalty of ethanol blends [8,29]. Kinetic studies show why. Hydroxyl radicals abstract a hydrogen atom from ethanol, mainly at the carbon bearing the OH group (R4), and the resulting α-hydroxyethyl radical reacts with oxygen through a low-barrier channel to give acetaldehyde and the hydroperoxyl radical (R5) [50,51]. Acetaldehyde is then oxidised further in the flame (R6); it escapes in quenched or unburned regions, notably during cold starts before the catalyst is warm, and is removed over a warm three-way catalyst (R7). In the atmosphere acetaldehyde follows R8–R10 to peroxyacetyl nitrate (PAN), an eye irritant and a temporary store of NO_2. An air-quality model of a U.S. fleet running E85 found higher PAN and, in some regions, higher ozone-related mortality than for gasoline [52]; that study concerned E85 rather than E10–E20, and its conclusion that E85 is unlikely to improve air quality is not a statement about low blends. Catalyst performance and fleet age therefore matter more than the ethanol percentage alone.

5.3 Formation of acetic acid

Acetic acid is not a component of the fuel but a product of ethanol oxidation, and it matters because it lowers the pH of the fuel and attacks metals. Three routes are recognised (Scheme 3).

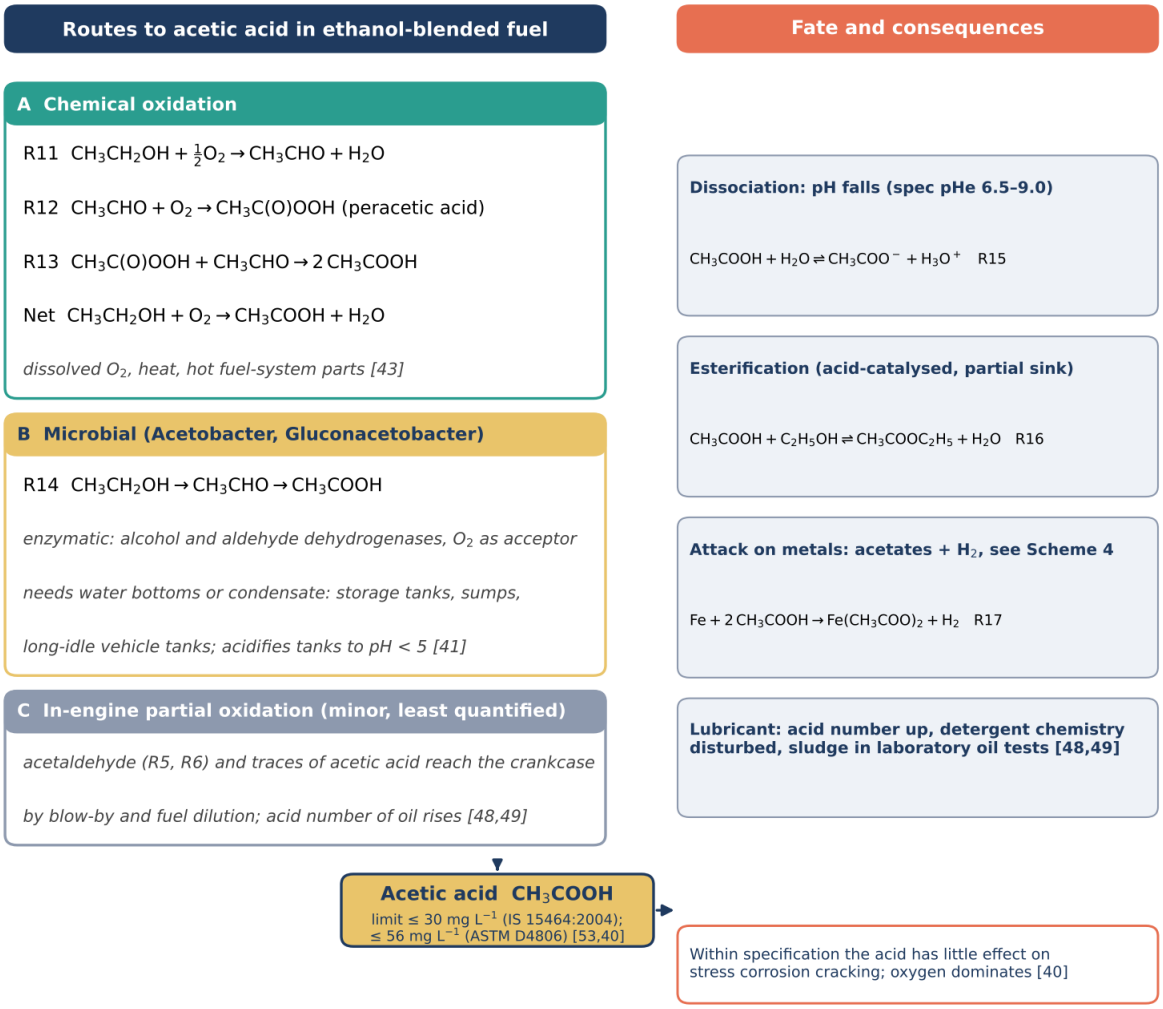
- **Chemical oxidation (route A).** Ethanol is oxidised by dissolved oxygen to acetaldehyde (R11); acetaldehyde adds oxygen to give peracetic acid (R12), which oxidises a second acetaldehyde to two molecules of acetic acid (R13). The net result is $CH_3CH_2OH + O_2 \rightarrow CH_3COOH + H_2O$. Water and acetic acid produced by ethanol oxidation in blended fuel were shown to have protective and corrosive effects respectively on an aluminium alloy in hot E20 [43]. The reaction is slow at ambient temperature and is favoured by oxygen, heat and long storage.

- **Microbial oxidation (route B).** Acetic-acid bacteria such as *Acetobacter aceti* convert ethanol to acetaldehyde and then to acetic acid (R14), using oxygen, and need an aqueous phase. They have been isolated from ethanol storage tanks, and *Acetobacter* and *Gluconacetobacter* dominated samples from tanks with pH below five [41]. In laboratory tests that simulated underground-tank sumps, acetic acid produced by *Acetobacter* corroded copper and steel severely, and steel samples lost wall thickness at roughly 1 mm per year in ethanol and acetic acid vapour [41]. This route is relevant to terminals, dispensers and long-idle vehicle tanks that hold a water layer, not to dry fuel in daily use.

- **In-engine partial oxidation (route C).** Acetaldehyde and traces of acetic acid formed in the cylinder can reach the crankcase through blow-by and fuel dilution. Laboratory work added ethanol, acetaldehyde and acetic acid to formulated engine oils: acetic acid, unlike ethanol, affected detergent chemistry and caused sludge, although bench tests on a passenger car showed no significant corrosion or wear of the parts [49]. This route is the least quantified.

Once formed, acetic acid dissociates (R15, pK_a 4.76 in water), partly esterifies with ethanol to ethyl acetate and water (R16), and reacts with metals (R17 and Scheme 4). Fuel specifications therefore limit acidity: 56 mg/L as acetic acid (0.007 mass %) with a pH_e range of 6.5–9.0 in ASTM D4806 as reported by API [40], and 30 mg/L in the Indian standard IS 15464:2004 for ethanol used in blending [53]. API's large study of stress corrosion cracking found that, within specification limits, acetic acid and pH_e had no adverse effect on cracking, whereas dissolved oxygen was the controlling factor [40]. Acetic acid is therefore best viewed as an aggravating factor for uniform corrosion of copper, zinc, iron and aluminium rather than as the cause of cracking.

Scheme 3. Formation and fate of acetic acid in ethanol-blended fuel (reactions R11–R17)



Note: routes A–C after [41,43,48,49]; specification limits from [40,53]. Routes A and B require oxygen; route B also requires a water phase.

5.4 Fuel-quality parameters that control the chemistry

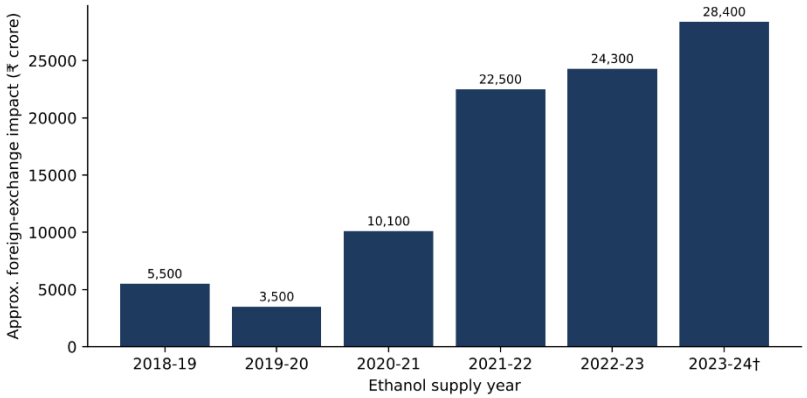
The reactions above are suppressed by a small number of specification limits. Indian standard IS 15464:2022 describes blending ethanol as at least 99.5 % ethanol with not more than 0.5 % water by volume [63]; the earlier 2004 edition limited acidity to 30 mg/L as acetic acid and aldehydes to 60 mg/L as acetaldehyde, with copper limited to 0.1 mg/kg [53]. Copper is limited because it is itself corroded and can contaminate fuel. Industry has asked for mandatory chloride limits in the Indian fuel standards, proposing less than 1 mg/kg for commercial E20 and E85 and less than 3 mg/kg for blending ethanol [56]; the corresponding U.S. ethanol limit was lowered from 32 to 8 mg/L in 2009 [40]. These numbers return in Sections 8 and 12.

6. Benefits of Ethanol–Petrol Blending

6.1 Energy security and foreign exchange

Domestic ethanol displaces imported crude. Indian parliamentary and industry data report an approximate foreign-exchange impact of ₹5,500 crore in ESY 2018–19, rising to ₹24,300 crore in 2022–23 [17] and ₹28,400 crore in 2023–24 (as on 30 September 2024) [27] (Figure 7). These are government-reported estimates and depend on crude and ethanol prices; they do not include all indirect costs, and savings accrue nationally rather than at the pump [57]. Brazil's move from E27 to E30 is intended to eliminate petrol imports and is expected to create an exportable petrol surplus of about 700 million litres a year [4].

Figure 7. Reported foreign-exchange impact of the EBP programme



Note: the 2023–24 figure (marked by a dagger in the plot) is as on 30 September 2024. Data: [17,27].

6.2 Octane enhancement and potential engine-efficiency gains

Ethanol is a high-octane blending component: low-octane blendstock plus 10 % ethanol can be used to reach standard 87-octane petrol in the U.S. [6]. Quantitative studies estimate that adding 10–20 % more ethanol to U.S. gasoline could raise RON by 4–7 points and allow compression-ratio increases of roughly 1–3 units [24]. Reviews of spark-ignition engine efficiency conclude that higher ethanol content provides additional efficiency benefits for part- and full-load operation, mainly when compression ratio and spark timing are adapted [25]. The benefit therefore depends on engine design: existing engines gain mostly in knock margin, while purpose-designed engines can convert octane into efficiency.

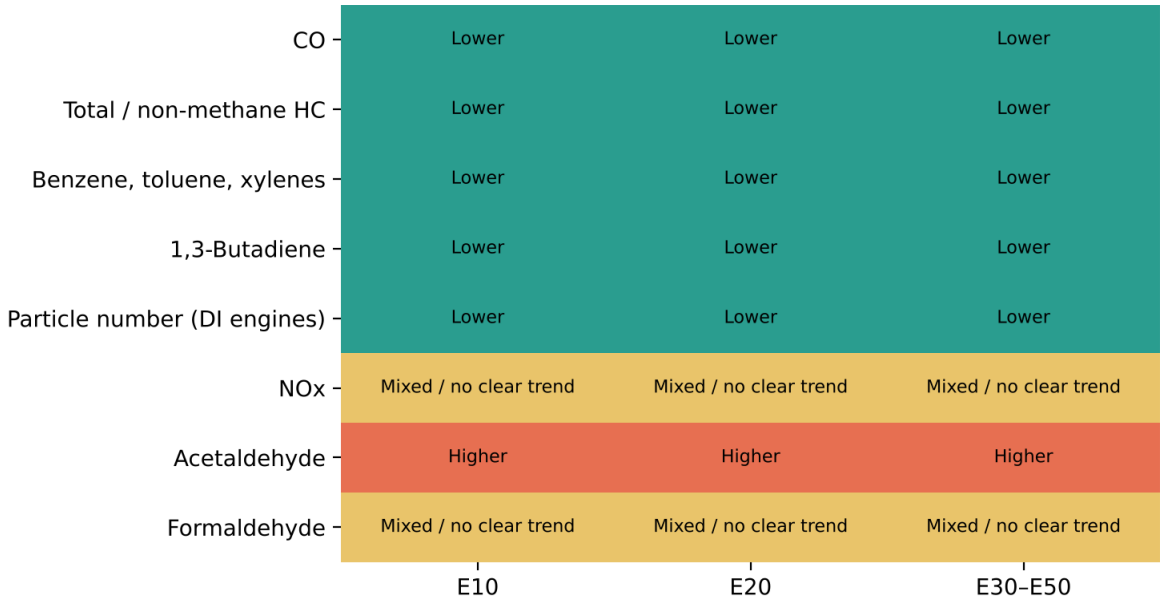
6.3 Tailpipe emissions

In U.S. Department of Energy tests of E10–E20 in legacy vehicles and small engines, increasing ethanol content reduced non-methane hydrocarbons and carbon monoxide while increasing ethanol and aldehyde emissions [28,29]. A California study of seven vehicles (1984–2007) on E10, E20, E50 and E85 found lower CO with all ethanol blends (with the largest reductions in older vehicles), generally lower THC and NMHC, and lower benzene, toluene, ethylbenzene, xylenes and 1,3-butadiene than reference fuel [8]. In direct-injection spark-ignition vehicles, E10 and E20 reduced particle number, with E20 lowering particles by about 40 % during a high-load cycle in one study [30,31], and an engine study found engine-out particulate decreasing with increasing ethanol content [32]. Table 4 and Figure 8 summarise the direction of effects; the chemistry behind the aldehyde rise is given in Scheme 2.

Table 4. Direction of tailpipe-emission response to ethanol blending (relative to E0)

Pollutant	Direction	Evidence	Sources
Carbon monoxide	Lower	Lower with ethanol blends for all vehicles tested; largest reductions in older vehicles (E10–E85)	[8,29]
Total / non-methane hydrocarbons	Lower (most cases)	Lower with ethanol blends in most cases; E85 raised THC in one flex-fuel vehicle	[8,29]
BTEX, 1,3-butadiene	Lower	Lower than reference fuel; almost undetectable for E85	[8]
Particle number (DI engines)	Lower	Reductions with E10, E20; engine-out particulate decreasing with ethanol; injection strategy dominates	[30–32]
Oxides of nitrogen	Mixed	Some older vehicles increased; others no or slight non-significant decrease	[8]
Acetaldehyde	Higher	Consistent increase with ethanol level (R4–R7)	[8,29]
Formaldehyde	No clear trend	Significantly higher only with E85	[8]
Carbon dioxide (tailpipe)	No clear trend	No significant trend in the fleet tested; ≈ equal per MJ (Scheme 2)	[8]

Figure 8. Directional tailpipe-emission response to ethanol (vs. E0)



Note: qualitative classification of the cited studies; magnitudes depend on vehicle technology, calibration and test cycle [8,28,30].

6.4 Greenhouse gases and rural economy

Indian government statements, citing NITI Aayog studies, report greenhouse-gas reductions of about 65 % for sugarcane-based ethanol and 50 % for maize-based ethanol compared with petrol [14]. Ethanol demand also supports sugar, grain and distillery sectors and creates new markets for surplus or damaged grain, as reflected in the shift toward maize as the largest feedstock in ESY 2024–25 [3]. Section 10 explains why life-cycle claims are contested.

6.5 Benefits that accrue to vehicle owners

Several benefits reach the owner directly, not only the nation:

- **Higher knock resistance.** Measured octane of regular E20 was 98.2 RON, essentially equal to the 98.8 RON of the premium grade [57]. Engines that retard timing to avoid knock in hot weather or under load regain margin, and engines with knock control and adaptable timing can use it.
- **Cleaner exhaust.** Lower CO and hydrocarbons, with the largest CO reductions in older vehicles [8], and lower particle number in direct-injection engines [30,31], reduce the owner's contribution to local pollution and the load on after-treatment.
- **Small mileage penalty in calibrated vehicles.** The government reports 1–2 % for vehicles calibrated for E20, against 3–6 % for others [14], and ARAI trials of 40,000 km in passenger cars and 20,000 km in two-wheelers are reported to have found no significant adverse effect on engine performance [55].
- **No damage found in roadmap vehicle trials.** The NITI Aayog roadmap trials recorded no severe malfunction, abnormal wear, deposits or oil deterioration after mileage accumulation on E20 [55]; metals showed insignificant corrosion in ARAI immersion tests [55].
- **Warranty and insurance assurances.** SIAM stated that manufacturers' warranties will be honoured for E20 use, whatever the owner's manual says [54], and ICICI Lombard clarified in June 2026 that E20 use does not invalidate motor insurance or, by itself, lead to rejection of an otherwise admissible claim [58].
- **Choice where flex-fuel is available.** Flex-fuel owners can select the blend by price, as in Brazil, where more than 80 % of cars are flex-fuel [61].

7. Disadvantages, Risks and Uncertainties

7.1 Lower energy density and consumer cost

Because ethanol carries less energy per litre, vehicles burn more litres per kilometre unless engines are re-optimised [6,7]. Where blended fuel is priced the same as lower-ethanol petrol, drivers bear the cost of the mileage penalty, a recurrent point of criticism in the Indian debate [15,16]; E20 is not cheaper at the pump because ethanol procurement, tax, transport and blending offset any saving [57]. Government figures put the E20 penalty at 1–6 %, while some users report larger drops, attributed by officials to maintenance, tyre pressure or driving style [14]; the independent tests in Figure 6 fall in between and above the government range for two of four cars [57].

7.2 Materials, corrosion and legacy vehicles

Ethanol-blended fuels swell and extract components from some elastomers and plastics, and the fuel chemistry of Section 5 can corrode some metals. Because this is the owner's main concern, it is treated separately in Section 8, and vehicle tolerance in Section 9.

7.3 Volatility, cold start and water

Ethanol's high heat of vaporisation complicates cold starts in high-ethanol fuels and changes distillation and vapour-pressure behaviour; vapour pressure can be managed by selecting a low-vapour-pressure base fuel [7]. Ethanol is fully water-miscible, and blends can phase-separate in the presence of excess water, with greater tolerance as ethanol content increases [7]. In a phase-separated tank the ethanol–water layer settles at the bottom and can be drawn into the engine [56]. For E5–E30 the practical issues are mainly distribution hygiene and storage; for E40–E50 and higher, cold-start strategies and flex-fuel calibration become more important.

7.4 Aldehydes, NOx and particles

The most consistent unregulated-emission penalty is higher acetaldehyde with increasing ethanol content (Scheme 2), and formaldehyde and acetaldehyde were significantly higher with E85 [8]. Effects on NOx are mixed and vehicle-dependent [8]. Particle emissions from direct-injection engines are much greater than from port-injection engines and depend strongly on injection timing; ethanol reduces but does not eliminate this problem [30,31].

7.5 Land use, food security and water

Crop-based ethanol competes for land and water. A global agricultural model concluded that diverting U.S. cropland to corn ethanol could increase greenhouse-gas emissions over decades once land-use change is counted [35]. An empirical assessment of the U.S. Renewable Fuel Standard estimated that it raised corn prices by about 30 %, expanded cropland, increased fertiliser use and water-quality degradants, and that corn-ethanol carbon intensity was no lower than petrol and likely at least 24 % higher [10]; the USDA Office of the Chief Economist has issued a critical technical review of that paper [36]. Bioenergy water footprints range from 1,400 to 20,000 L of water per L of biofuel across crops and countries, with bioethanol generally lower than biodiesel [37]. These findings are from the U.S. and global contexts; India-specific peer-reviewed estimates for sugarcane and maize ethanol should be developed because sugarcane is water-intensive and maize competes with feed and food demand.

8. Corrosion of Engines and Fuel Systems, Materials and Lubricants

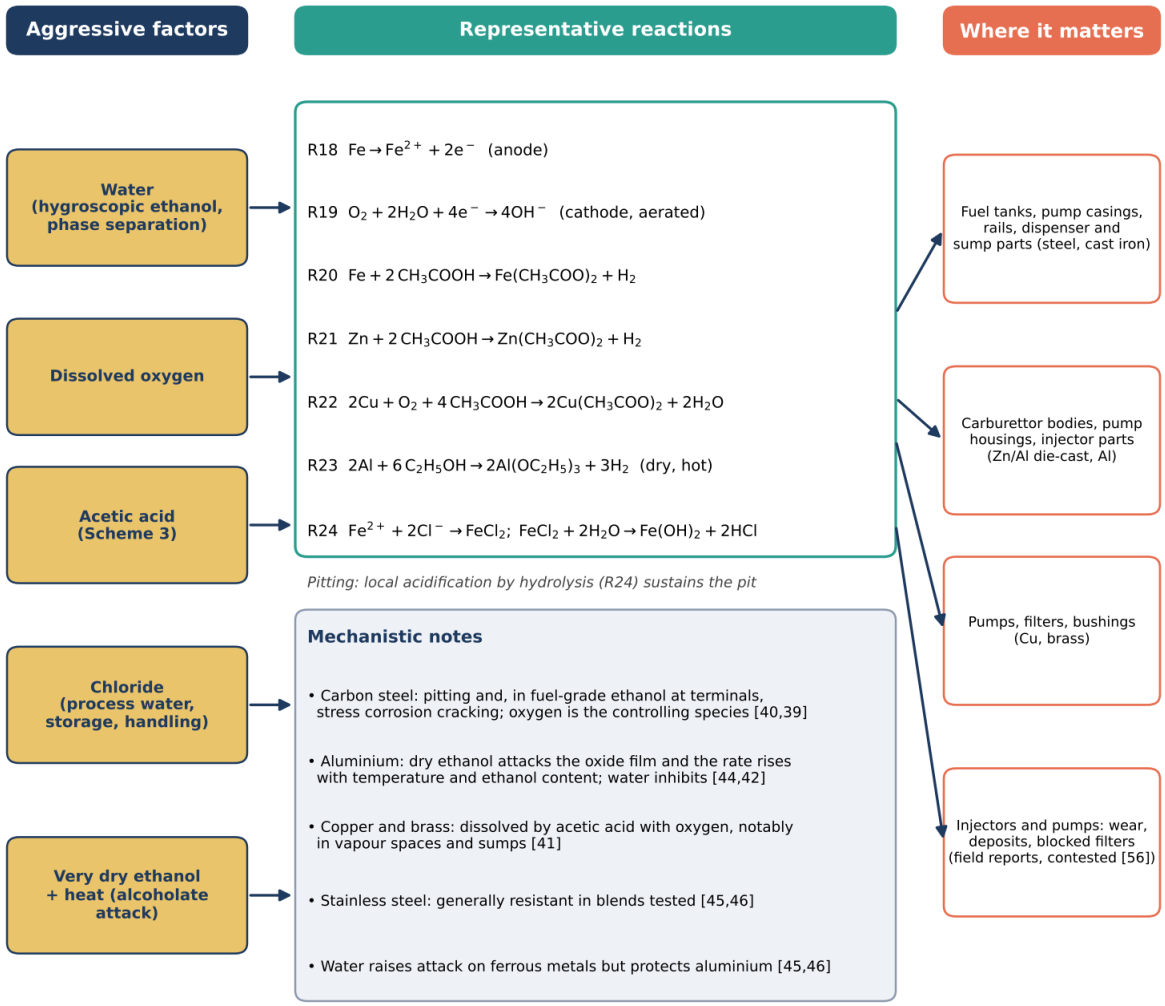
8.1 Mechanisms

Ethanol is a protic solvent that is fully miscible with water, and its blends absorb moisture; water, dissolved oxygen, acetic acid (Scheme 3) and chloride then supply the ingredients of electrochemical corrosion (Scheme 4). On iron, the anodic and cathodic steps are R18 and R19, acetic acid adds direct dissolution (R20), and chloride sustains pits through hydrolysis that acidifies the pit (R24). Zinc and copper are attacked by acetic acid, copper in the presence of oxygen (R21, R22). Aluminium is passive in water-containing fuel but, in very dry ethanol at elevated temperature, the oxide film is attacked and corrosion proceeds, which is commonly written as formation of aluminium ethoxide (R23) [44]. Water slows this attack, so the water that promotes corrosion of steel tends to protect aluminium [42,44–46].

For carbon steel, laboratory studies establish that pitting and stress corrosion cracking occur in fuel-grade ethanol, and that dissolved oxygen is the controlling variable: when oxygen was removed by nitrogen purging no cracking occurred, even with other species at their specification limits [40].

Cracking has been observed mainly in terminal storage tanks and loading racks handling ethanol before blending, not in ethanol producers' tanks or in vehicles [40]. Water, acetic acid and chloride change the corrosion rate and pitting of carbon steel [39]. The corrosion-rate inhibitor tested by API lowered the corrosion rate of steel but did not prevent cracking [40].

Scheme 4. Corrosion factors, representative reactions and affected components in ethanol-blended fuel (reactions R18–R24)



Note: reactions are the standard electrochemical and acid–metal reactions expected under these conditions; R23 follows the alcoholate-corrosion description for aluminium in dry ethanol [44]. Rates depend on water, oxygen, temperature and chloride; most data are from laboratory immersion or electrochemical tests.

8.2 Which materials are affected

Table 5 sets out behaviour by material class. The overall pattern is that carbon steel and copper are the susceptible metals, stainless steel is resistant in the blends tested, aluminium is sensitive mainly to dry, hot, high-ethanol fuel, and rubber and plastic components are the most common compatibility concern in older vehicles. For zinc die-castings, used in older carburettors and pumps, the open literature identified here is thin, so the entry rests on the acid chemistry (R21) rather than on vehicle data.

Table 5. Behaviour of fuel-system materials in ethanol-blended fuel

Material	Typical parts	Behaviour	Sources
Carbon / mild steel	Tanks, rails, pump casings, dispenser and sump parts	Uniform and pitting corrosion; stress cracking in fuel-grade ethanol, controlled by excluding oxygen; acetic acid and chloride increase attack	[39,40,45]
Stainless steel	Fuel lines, fittings, filters	Compatible in blends tested up to high ethanol; ARAI found insignificant corrosion of the metals tested in E20 immersion	[45,46,55]
Aluminium alloys	Carburettor bodies, pump housings, injector and engine parts	Attack rises with temperature and ethanol content in dry fuel; water inhibits; acetic acid and oxygen effects documented	[42–44]
Zinc die-cast alloys	Older carburettors and fuel pumps	Expected attack by acetic acid (R21); few direct data in the literature reviewed	[Section 5]
Copper and brass	Pump parts, bushings, filters	Susceptible, severely corroded by acetic acid vapour with oxygen; copper in fuel is itself limited to 0.1 mg/kg	[41,45,53]
Elastomers	Hoses, O-rings, gaskets, diaphragms	Swell then shrink after drying as plasticisers are extracted; ARAI found E20 effects greater than E10 on NBR-PVC and epichlorohydrin	[9,55]
Plastics	Pipes, tank liners, connectors	Retain fuel; ARAI found greater tensile-strength and volume change of PA66 in E20 than in E10	[9,55]
Metals overall (volume change)	Mixed metals	Least affected group in a university study, with changes of 6 % or less	[9]

8.3 Elastomers and plastics

Elastomers generally swelled after exposure and then shrank after drying as plasticisers were extracted, plastics retained fuel, and metals were the least affected, with volume changes of 6 % or less [9]. Oak Ridge studies exposed metals, elastomers, sealants and plastics to aggressive formulations of E10–E25 and later to E50 and E85 [12,33]. ARAI's 2021 study of eight metals, six elastomers and four plastics found the effect of E20 on metals insignificant, but a greater effect than E10 on an NBR-PVC blend and on epichlorohydrin, and a greater change in tensile strength and volume of polyamide 66, materials used in gaskets, seals, O-rings, hoses and pipes [55]. The government says that only some older BS-III vehicles manufactured between 2005 and 2016 may need earlier replacement of rubber parts and gaskets on E20 [15,16]. The roadmap recommended continued availability of lower blends for older vehicles during the transition [11,34]; in practice E10 is no longer sold as a separate retail grade in India [57].

8.4 Engine oil

Ethanol that dilutes the crankcase oil lowers viscosity and raises acid number. A four-ball wear study of fully synthetic oil diluted with E0, E10, E20, E30 and E85 found higher friction and wear for all diluted samples, with E10 having slight effects [48]. Acetic acid affected detergent chemistry and formed sludge in laboratory oil tests, but chassis-dynamometer bench tests found no significant corrosion or wear of engine parts [49]. These studies suggest a case for following the manufacturer's oil-change interval, and not extending it, particularly in short-trip use where condensate and fuel accumulate; they do not show damage under normal use.

8.5 Contamination in the Indian supply chain

In mid-2026 manufacturers reported to the Ministry of Petroleum and Natural Gas a rise in replacement of fuel injectors, fuel pumps and other fuel-wetted parts, which field investigations linked to corrosion and wear from chloride and moisture contamination. Samples from vehicle tanks showed chloride up to 500 mg/kg and from retail outlets up to 350 mg/kg, and water above 10,000 mg/kg in some samples against a permissible 3,000 mg/kg; ageing storage tanks, pipelines and tankers were identified as likely sources [56]. The Ministry replied that it tests for water ingress 8–12 times a day at more than 87,000 outlets, had tested over 2,000 samples for chloride and sulphide and found only two chloride cases, whose sales were suspended [56]; a SIAM letter carrying the chloride figures was later withdrawn, according to press accounts [57]. Toyota attributed one reported engine problem to contaminated fuel rather than to E20 [55].

The evidence is therefore contested, and the figures above are industry-reported, not independently verified. Two points are consistent with the laboratory science. First, API's findings and the electrochemical studies indicate that, within specification, the metals are not the weak point; excess water, oxygen, acid and chloride are [39,40]. Second, the same ARAI study that found metals unaffected found that some rubber and plastic parts are [55]. In the author's reading, ethanol content and fuel-handling quality are separate variables, and sound chloride and water control matters as much as the blend level. Independent audits of retail fuel would settle the matter.

9. Which Vehicles Tolerate Which Blends

Tolerance depends on three things: whether the engine control system can adapt to the extra oxygen, whether the materials of the fuel system were qualified for ethanol, and whether the blend is within what the manufacturer or regulator has approved. Figure 9 and Table 6 summarise the position; the classification is the author's synthesis of the cited statements, not a certification, and the owner's manual or the manufacturer prevails.

Figure 9. Vehicle tolerance map for E10 to E85 (author's synthesis)

	E10	E15	E20	E25–E30	E50	E85
Flex-fuel vehicles (factory FFV)	Designed for	Designed for	Designed for	Designed for	Designed for	Designed for
India: petrol vehicles built for E20 (from April 2023)	Designed for	Designed for	Designed for	Check	Not advised	Not advised
US: conventional light-duty, model year 2001 and newer	Designed for	Designed for	Not advised	Not advised	Not advised	Not advised
India: petrol cars built for E10 (BS-IV / early BS-VI, before 2023)	Designed for	Check	Check	Not advised	Not advised	Not advised
Older carburetted vehicles and classics (pre-BS-III, pre-2001)	Check	Not advised	Not advised	Not advised	Not advised	Not advised
Motorcycles and scooters not certified for E20	Designed for	Check	Check	Not advised	Not advised	Not advised
Small engines and marine (mowers, saws, outboards)	Designed for	Not advised	Not advised	Not advised	Not advised	Not advised

Note: "Designed for" = approved or built for that blend; "Check" = depends on manufacturer statement, model year and condition of rubber and plastic parts; "Not advised" = not approved or no basis for use. Sources in Table 6.

Table 6. Vehicle categories, evidence and practical position

Vehicle category	Evidence and statements	Practical position
Flex-fuel vehicles (FFV)	Designed to run on gasoline or any blend up to 83 % ethanol; sensors adjust for fuel composition [47]. In Brazil more than 80 % of cars are flex-fuel [61].	Any blend E0–E85. Check the fuel-cap or badge marking.
India: built for E20 (from April 2023)	Government roadmap required E20-compatible new petrol models from April 2023 [57]; materials include some headroom against higher blends [55]. BIS standards for E22–E30 notified in 2026; ARAI studying E25 [19,57].	E10 to E20 designed for; confirm with the manufacturer before using E25–E30. Not for E50 or E85 unless flex-fuel.
US: conventional light-duty, 2001 and newer	Approved for up to E15; any blend above E15 only in FFVs [5,47].	E10–E15. E20 is not approved for non-FFV vehicles.
India: built for E10, before 2023	Several manufacturers state "material compliance" earlier: Honda cars made in India since 2009, Mercedes-Benz since 2005, Tata, Mahindra, Hyundai, Volkswagen and Skoda since April 2020, Renault and Nissan since April 2021; Toyota cars from April 2023, and the Toyota manual specifies E10 [54]. Government: only some older BS-III vehicles (2005–2016) may need rubber parts replaced [15,16]. ARAI: greater effect on NBR-PVC, epichlorohydrin and PA66 than E10 [55]. Independent tests show mileage losses of 5–12 % in two such cars [57].	Usually usable on E20 under the manufacturer's statement; inspect hoses, seals and gaskets and fuel filter; E25 and above not advised without manufacturer confirmation.
Older carburettor vehicles and classics (pre-BS-III, pre-2001)	No manufacturer E20 statements; designed for E0 or low blends; carburettors and mixed fuel-system materials; open-loop mixture runs leaner as ethanol rises [28,29]. About 80 % of petrol vehicles sold in India in the last 15 years are not E20-compliant [62]; 75–80 million pre-BS4 motorcycles are estimated to be in use [54].	Vulnerable. E10 at most where available; retrofit ethanol-grade parts; ethanol-free 100-octane petrol is an option for classics [57].
Motorcycles and scooters not certified for E20	U.S.: E15 not approved for motorcycles [5]. India: Honda says all two-wheelers from April 2025 are E20-ready and older models are material-compatible; Bajaj says its older products are material-compliant back to BS-IV (2017); TVS since 2023; Hero from April 2023, with marginal mileage impact on BS-III and BS-IV models [59].	Check the maker's statement for the model-year; air-cooled carburettor engines are most at risk of leaning; expect some mileage loss.
Small engines and marine (mowers, saws, outboards)	U.S.: E15 not approved for off-road engines [5]; DOE tests found small non-road engines may have trouble with higher blends [28].	E10 at most unless the manual says otherwise.

Two cautions apply. The exact cut-off years are manufacturers' own statements reported in 2025–2026 and have not been independently tested, and ARAI's full report on 2005–2021 vehicles has not been published because it contains manufacturer-sensitive data [54]. Second, DOE tests on 13 late-model U.S. vehicles found that about half showed higher catalyst temperature under full-throttle enrichment on E15–E20 because their calibration did not adapt [28]; an Australian study of E20 reported catalyst deterioration over 50,000 miles in most test vehicles, though those vehicles may have had different calibrations from U.S. ones [29]. Calibration, as much as material, decides tolerance. Brazilian experience is encouraging but not directly transferable: a lubricant specialist there states that the historical engine failures were concentrated in dedicated pure-alcohol vehicles on E100 [60], and Brazil's fleet is largely flex-fuel [61].

10. Life-cycle Greenhouse-gas Claims: Why They Differ

Published carbon-intensity estimates for crop ethanol differ widely, chiefly on whether and how indirect land-use change and soil carbon are counted (Table 7). Official Indian statements cite large reductions

[14], whereas high-profile U.S. studies find small or negative benefits for corn ethanol under land-use-change assumptions [10,35], and the latter has itself been disputed [36]. A reviewed body of literature on corn-ethanol carbon intensity also exists [38]. A balanced reading is that climate benefit is real in the best cases (for example by-product-rich sugarcane processing and waste-based feedstocks) but is not guaranteed and should be verified region by region. As Scheme 2 shows, tailpipe CO_2 per unit of energy is essentially unchanged, so the benefit lies wholly in the biogenic carbon cycle.

Table 7. Contrasting statements on ethanol greenhouse-gas performance

Source	Statement (paraphrased)	Context / caveat
NITI Aayog studies as cited by the Government of India [14]	GHG emissions about 65 % lower for sugarcane ethanol and 50 % lower for maize ethanol than petrol	Indian official statement; underlying boundary conditions not reproduced here
Searchinger et al., 2008 [35]	Corn ethanol could nearly double GHG over 30 years once land-use change is included	Model-based; depends on land-use-change assumptions
Lark et al., 2022 [10]	U.S. corn-ethanol carbon intensity no less than petrol and likely at least 24 % higher	Disputed by USDA OCE review [36]
Scully et al., 2021 [38]	State-of-the-science review of corn-ethanol carbon intensity	Cited in industry rebuttals to Lark et al.; readers should consult the paper for its figures

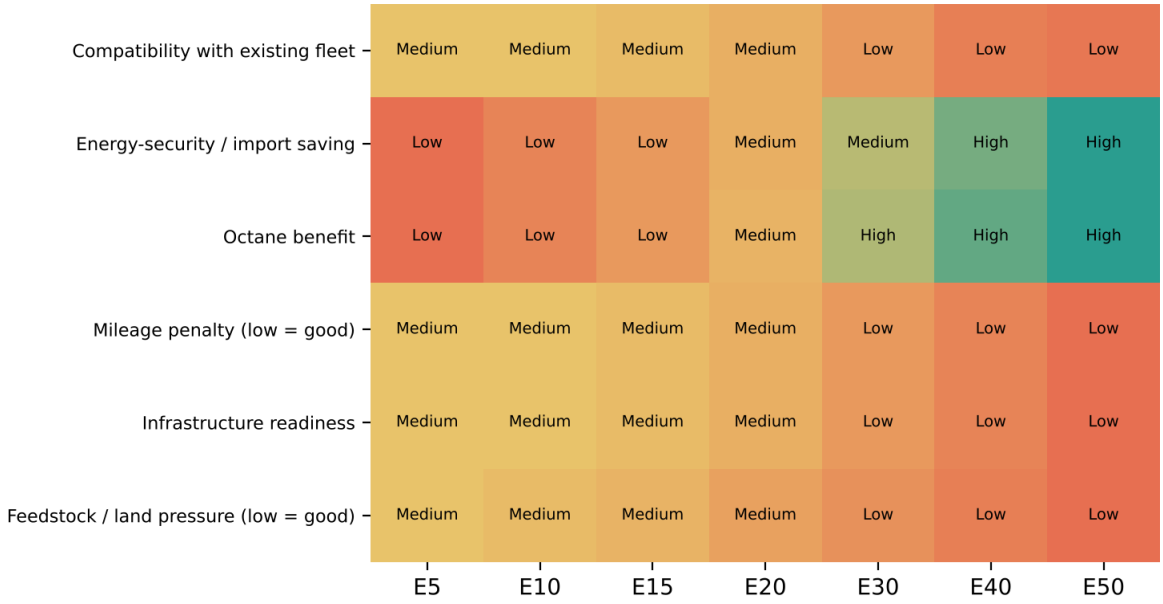
11. Blend-by-Blend Assessment: E5 to E50

Table 8, Figure 10 and Scheme 5 integrate the evidence by blend level. The ratings in Figure 10 are the author's qualitative synthesis for discussion, not measurements, and should be tested with fleet-specific data.

Table 8. Summary of benefits and disadvantages by blend level

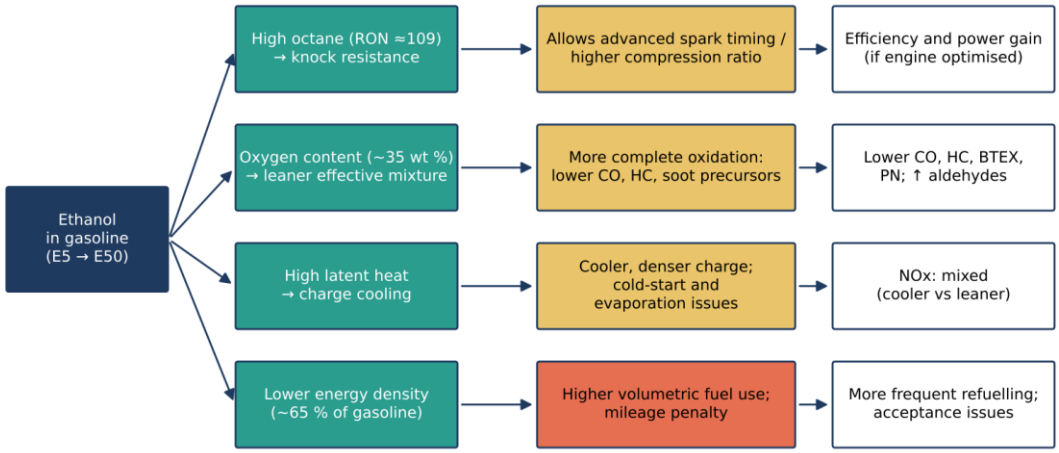
Blend	Main benefits	Main disadvantages / limits	Best suited to
E5	Small energy-security gain; negligible compatibility risk; modest octane gain	Small impact on imports and emissions	Entire fleet, including oldest vehicles
E10	Established standard; octane boost; lower CO and HC in older vehicles [6,8]	Roughly 3 % less energy per litre by linear estimate; higher aldehydes [8]	Entire modern fleet; baseline fuel for legacy vehicles
E15	More displacement of petrol; higher octane; approved for 2001+ U.S. light-duty vehicles [5]	Not approved for motorcycles, older vehicles, small engines in the U.S.; labelling needed [5]	Compatible light-duty fleets
E20	Large import saving; better octane; India's mainstream blend [2,11]	Mileage penalty of 1–6 % reported, larger in some independent tests; rubber and plastic parts in some older vehicles [14,15,55,57]; fuel-quality control critical [56]	Vehicles built or calibrated for E20; E10 should remain available for older vehicles [34]
E30	Very high octane; efficiency potential in optimised engines; Brazil regular petrol [4,25]	About 10 % lower energy per litre by linear estimate; more mileage loss in non-optimised engines; materials qualification	Flex-fuel or calibrated fleets; countries with established ethanol supply
E40–E50	Maximum octane and cooling; largest petrol displacement; lower PN [22,32]	Largest energy-density penalty (about 14–17 % by linear estimate); cold-start, material, supply and land-use pressure [7,12]	Dedicated flex-fuel vehicles and research programmes

Figure 10. Qualitative assessment of blend levels (author's synthesis)



Note: author's qualitative synthesis based on the evidence reviewed above; 'High', 'Medium' and 'Low' describe the relative strength of each criterion, with green indicating a favourable position.

Scheme 5. Mechanism of action: how ethanol alters spark-ignition engine behaviour and emissions



Note: mechanism-of-action scheme linking ethanol's properties (octane, oxygen content, latent heat and energy density) to engine behaviour and emissions [7,8,25,30]; the reaction steps are in Schemes 2–4.

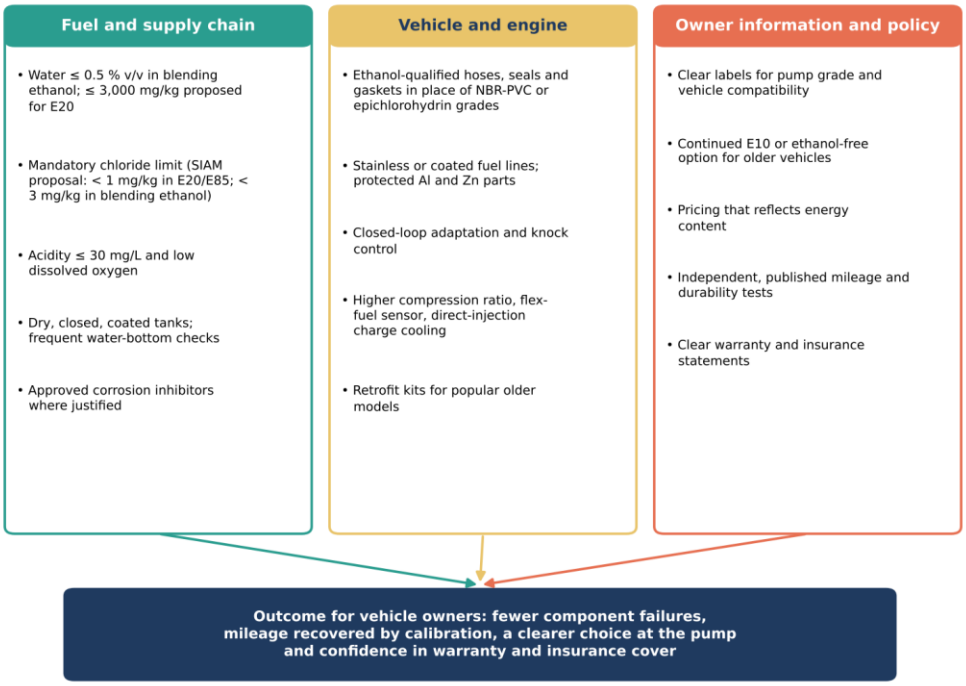
12. Improvements That Are Possible

Most of the disadvantages identified are engineering and quality-control problems with known remedies. Scheme 6 groups them under three heads.

12.1 Fuel and supply chain

- **Tight water control.** Blending ethanol is specified at no more than 0.5 % water [63]; a limit of 3,000 mg/kg in finished E20 is described as permissible, and levels of 7,000–10,000 mg/kg were reported in some samples [56]. Closed, dry, regularly drained tanks and frequent water-bottom checks address this.

Scheme 6. Routes to improvement: Fuel and supply chain, vehicle and engine, owner information and policy



Note: Test reports and industry proposals [9,12,24,25,40,53,55–57,63].

- **Mandatory chloride limits.** The Indian standards do not yet carry a mandatory chloride limit for finished E20; industry has proposed less than 1 mg/kg [56]. API data show that oxygen is the cracking driver and that the chloride limit was tightened in the U.S. to 8 mg/L [40].
- **Low acidity and oxygen.** Acidity limits of 30 mg/L (IS 15464:2004) or 56 mg/L (ASTM D4806) [40,53] and low dissolved oxygen cut both oxidation to acetic acid (R11–R14) and the cracking risk of steel [40]. NIST noted that its sump-corrosion test could be used to evaluate protective coatings and biocides [41].
- **Corrosion inhibitors.** API found that an inhibitor lowered steel corrosion rate but did not prevent cracking [40]; inhibitors complement, and do not replace, oxygen and water control.

12.2 Vehicle and engine

- **Ethanol-qualified materials.** Replace NBR-PVC and epichlorohydrin hoses, seals and gaskets, and review PA66 parts, with grades qualified for ethanol blends, using the compatibility data of [9,12,33,55]. Autocar India reports that official manufacturer kits are so far limited, that third-party parts exist, and that the cost falls on the owner [55,57].
- **Calibration and hardware.** Closed-loop adaptation and knock control let an engine use ethanol's octane; raising compression ratio by 1–3 units captures efficiency, offsetting the energy deficit [24,25]. Flex-fuel sensors let the engine identify the blend [47].
- **Protected metals.** Stainless or coated fuel lines and protected aluminium and zinc castings reduce attack; newer E20-compliant vehicles are reported to use ethanol-compatible materials [57].
- **After-treatment.** A well-functioning, warm catalyst removes most acetaldehyde (R7); quicker catalyst light-off addresses the cold-start gap.

12.3 Owner information and policy

- **Labelling and choice.** Clear pump and fuel-flap labelling, and an E10 or ethanol-free option for older vehicles as recommended by the roadmap [11,34]. A parallel supply chain is costly; the 100-octane grade is the practical ethanol-free route at present [57].

- **Pricing and transparency.** Consider pricing that reflects energy content, publish independent mileage and durability data, and release ARAI's test reports with sensitive data redacted [15,16,54].
- **Clear warranty and insurance statements.** Written confirmation from manufacturers and insurers, as already issued by SIAM and ICICI Lombard [54,58], should be extended to all categories.
- **Staged increases.** ARAI's study of E25 in E10- and E20-compatible vehicles, and the BIS E22–E30 standards, should be completed, and the findings made public, before any move beyond E20 [19,57].

13. Practical Guide for Vehicle Owners

Table 9 collects the actions an owner can take, each tied to the evidence above. Items marked "precaution" are the author's practical inference from the chemistry in Sections 5 and 8, not a manufacturer instruction.

Table 9. Owner checklist for ethanol-blended petrol

Action	Why / evidence	Applies to
Find out what your vehicle is rated for	Fuel-flap label, owner's manual or authorised dealer; compatibility varies with model and year, and some makers state material compliance earlier than April 2023 [54,57]	All petrol vehicles
Keep service records and fuel receipts	SIAM states warranties will be honoured for E20 use [54]; ICICI Lombard states E20 use does not invalidate cover, though damage claims still depend on the policy terms [58]	All vehicles
Inspect rubber and plastic fuel parts	ARAI found greater deterioration of NBR-PVC, epichlorohydrin and PA66 than on E10 [55]; inspect hoses, O-rings and gaskets more often, and replace worn parts with ethanol-grade ones	Pre-2023 vehicles, especially pre-2016
Replace the fuel filter on schedule or earlier	Precaution: Ethanol is a solvent and can carry loosened deposits and corrosion products to the filter; inspection more often is advised [57]	Older vehicles
Use fuel from busy, reputable outlets	Water and chloride in contaminated fuel are the most credible corrosion drivers [39,40,56]; if hard starting or misfiring follows a fill-up, keep the receipt and report the outlet	All vehicles
Do not leave a vehicle idle for long periods	Precaution: ethanol absorbs moisture, and a water layer allows acid-forming bacteria and corrosion [41,57]; run the vehicle regularly	Seasonal, classic and second vehicles
Follow the oil-change interval	Fuel dilution raises oil acid number and lowers viscosity [48,49]; do not stretch intervals in short-trip use	All vehicles
Manage mileage	Tyre pressure, servicing and driving style matter, as officials note [14]; expect larger losses in some vehicles (Figure 6) [57]	All vehicles
Consider ethanol-free 100-octane petrol for classics	Sold as XP100 and Power100; costs more and is sold in limited volumes [57]	Classic, high-performance older vehicles
Use upgrade kits only through authorised workshops	Official kits are limited; third-party parts exist at the owner's cost [55,57]	Pre-2023 vehicles

14. Challenges and Recommendations

- **Fleet segmentation and choice.** Keep E10 (or lower) available for legacy vehicles and motorcycles not designed for E20 or higher, in line with the roadmap's recommendation [11,34], and label pumps clearly.
- **Independent real-world testing.** Publish transparent, repeatable fuel-economy, durability and emission data for E20 and E22–E30 across Indian two-wheelers, cars and light commercial vehicles, since public statements rely on summarised studies [14–16,54].
- **Fuel quality and corrosion control.** Adopt mandatory chloride limits, enforce water limits and audit retail fuel independently; a laboratory-proven link between chloride, water and component failure is more actionable than a debate about ethanol [39,40,56].
- **Materials and infrastructure.** Qualify dispensers, tanks, seals and onboard fuel-system components for the intended blend, drawing on U.S. compatibility data up to E50 and ARAI data for E20 [9,12,33,55].
- **Engine optimisation.** Pair higher blends with higher compression ratio and flex-fuel calibration so that octane gains offset the energy deficit [24,25].
- **Pollution control.** Monitor aldehydes, NOx and particle number from direct-injection engines on higher blends, and specify after-treatment accordingly [8,31,52].
- **Feedstock and sustainability.** Diversify toward residues and non-food feedstocks, and develop India-specific life-cycle, land-use and water-footprint assessments rather than relying on foreign studies [3,10,35,37].
- **Pricing and consumer communication.** Communicate expected mileage change honestly, and consider whether pricing should reflect energy content, since this is a main source of public dissatisfaction [15,16,57].

15. Conclusions

Ethanol–petrol blends from E5 to E50 form a continuum of risk and reward. E5–E10 are well established and broadly compatible. E15–E20 deliver substantial import substitution and octane enhancement and are feasible for suitably designed or calibrated vehicles, but entail a measurable mileage penalty (government-reported 1–6 %, 4–13 % in four independent tests), material-compatibility considerations for older vehicles and unresolved debate on life-cycle benefits. The chemistry shows that acetaldehyde is the characteristic combustion by-product and that acetic acid forms slowly by oxidation, faster where bacteria and water are present, and aggravates corrosion of steel, copper, zinc and aluminium. Laboratory evidence points to oxygen, water, acid and chloride, not ethanol itself, as the drivers of metal corrosion, and to rubber and plastic parts as the weak point of older vehicles. E30–E50 offer the greatest octane and displacement potential and are already mandated in Brazil at E30 [4], but they require flex-fuel capability, materials qualification, careful calibration and sustainable feedstock supply. For vehicle owners the position is reassuring for vehicles built for E20 and manageable for many older ones with inspection and part replacement, but vulnerable for classics and small engines. For India, the principal task now is to combine the programme's scale with transparent real-world data, strict control of water and chloride in retail fuel, protection of legacy-vehicle owners and credible, region-specific sustainability accounting.

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