LETTER

A quick and low E-factor waste valorization procedure for CuCl-catalyzed oxidative self-coupling of (hetero)arylboronic acid in pomegranate peel ash extract

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ABSTRACT

The application of waste biomass-derived materials to synthetic chemistry is a remarkable achievement, and the use of aqueous media is further advancement. The switch towards earth’s abundant metals like cobalt/copper/iron/nickel from precious palladium in C–C coupling reactions is also a high throughput in the global sustainability perspective. Herein, we describe a CuCl-catalyzed homocoupling of (hetero)arylboronic acids (HABAs) in water extract of pomegranate ash (WEPA) with low E-factor of 1.25 without including the column chromatographic separation of products, which helped in understanding the effectiveness of this method on comparison to reported protocols lacking amounts of silica gel and eluents, however, it was 171.64 by including column purification. The reactions are conducted at room temperature to deliver self-coupling products with 90–99% yields in 10–45 min under precious metal, ligand, non-renewable base, toxic/problematic organic solvent and added oxidant-free conditions. A wide range of substrates were screened with aryl and heteroaryl moieties containing diversified functional groups. The substitution of earth’s rare metals-based catalysts by abundant copper, exploration of waste to state-of-the-art C–C coupling, use of biorenewable base, aqueous media, ambient conditions, operational simplicity, excellent yields of biaryls and quick reactions are the noteworthy advantages of this protocol.

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1. Introduction

The effective utilization/disposal of solid waste produced by the rapid urbanization and rise of living standards is an urgent and highly needed task for the sustainability of environment and human life (1). Further, the solid organic waste is the major contributor to the greenhouse gas (GHG) emission (1). In this connection recently the scientific community has been working on the utilization of solid waste ash-derived aqueous medium for synthetic organic chemistry (1,2). Besides the effective use/disposal of solid organic waste, these processes are also associated
with the application of nature’s most preferred solvent such as water as the reaction medium ([1],2). In several reports these biorenewable ash-derived aqueous extracts act as catalysts/reagents or bases. Therefore, these procedures cover the most of the constituent principles of Green Chemistry. Inspired by our recent work on these extracts ([1],3–5) we report here a sustainable Cu-catalyzed self-coupling reaction of (hetero)aryl-boronic acids [(H)ABAs] using water extract of pomegranate ash (WEPA) as a biorenewable base and reaction medium.

Biaryls are the prevalent pharmacophoric substances that are found in the wealth of therapeutics which include anti-inflammatory, antibiotic, analgesic, antihypertensive and neurological drugs ([6,7,8]). The importance of biaryl scaffolds in pharmaceutics has been identified by their ability in interacting with diverse functionalities which are extensively available in biological target molecules ([7,8,9]). Due to the selective binding capability to proteins, these biaryl scaffolds are considered as privileged structures ([9]). Mostly, the biaryls were synthesized by precious palladium-catalyzed processes for example Suzuki reactions (1,2,10,11), modified Ullmann reactions (1,12,13), Hiyama reactions (14,15) and Kumada (16,17) reactions. The self-coupling of organoboron compounds is an alternative, straightforward and easy strategy to synthesize biaryls, but very limited studies appeared in the literature on this area ([5,18,19]). Palladium-based catalysts are reported in most of the available methods of self-coupling reactions of organoboron compounds ([5,18–23]). Gold ([24–28], ruthenium ([29,30]) and rhodium ([31]) based catalysts are also employed infrequently for this purpose. The application of copper-based catalysts replacing the precious metals such as palladium, gold, ruthenium and rhodium has also been reported for the self-coupling of organoboron compounds ([32–37]). But most of these methods require toxic/problematic solvents ([32,34,35,37], unconventional catalysts ([32–35,37], tedious preparation of catalysts ([32–35,37], requirement of non-renewable base ([33]), heating ([32,34]), large reaction times ([32,33,35–37] and ligands/additives ([32–37]). Hence, the development of new protocols for self-coupling of (H)ABAs under mild conditions in aqueous media using simple and readily available Cu-based catalysts is highly inevitable.

A brief review of the existing strategies along with a comparative analysis of advantageous oxidative self-coupling reactions of organoboron compounds is displayed in Scheme 1 and Table 1. As can be seen, this protocol shows clear merits against the reported protocols like the use of non-precious CuCl as a catalyst, ambient conditions, application of biorenewable material, quick reactions, use of aqueous media, avoidance of non-renewable resources based solvents/promoters and wide substrate scope.

Moreover, the recently considered green metric, environmental factor (E-factor) indicates that the non-recyclable substances in the development of a new process/method can be considered as waste ([38–40]). The water and other recyclable substances such as solvents, substrates, reagents and catalysts are not considered to be waste. Therefore, the estimation of the E-factor for a developed process can describe the effectiveness of the process toward environmental sustainability and the development of protocols with a low E-factor is highly favored ([38–40]). Hence, toward developing a low E-factor protocol for self-coupling of (H)ABAs, the

![Scheme 1. Brief overview on self-coupling reactions of organoboron compounds.](image-url)
present CuCl-catalyzed procedure is found to be highly useful. Moreover, this method displayed a low E-factor over the other reported methods (Table 1).

### 2. Materials and methods

#### 2.1. General information

The (H)ABAs were procured from AVRA Synthesis, Sigma-Aldrich and Alfa Aesar and employed without any purification. Thin layer chromatography (TLC) has been used to know the progress of self-coupling reactions of (H)ABAs by employing varying ratios of ethyl acetate and n-hexane, and the improvements in reactions were visualized using UV light. $^1$H NMR and $^{13}$C NMR spectra have been obtained using JEOL, JNM ECS NMR instrument operating at 400/100 MHz employing the solvent, CDCl$_3$ and internal standard, tetramethylsilane (TMS). The chemical shift ($\delta$) and coupling constant ($J$) values were provided in ppm and hertz (Hz).

#### 2.2. Procedure for the preparation of WEPA

The reported procedure of our previous publications (3–5,13) was employed for the preparation of WEPA.

#### 2.3. Procedure for the CuCl-catalyzed self-coupling of (H)ABAs using WEPA

To a solution of (H)ABA (1) (1 mmol) in 1 mL of WEPA and 0.5 mL of EtOH was added 5 mol% of CuCl and the reaction mixture was stirred at RT. After the completion of the reaction (Table 2), ethanol was evaporated. To the residue was added 5 mL of water. The crude biaryl was extracted from the aqueous mixture into ethyl acetate. The ethyl acetate mixture was then afforded the symmetrical biaryl, 2 using silica-gel packed column chromatography. In some cases, the products obtained during ethyl acetate extraction are sufficiently pure so that purification by column chromatography is not needed (Table 3). The structures of symmetrical biaryls have been confirmed by $^1$H NMR, $^{13}$C NMR and mass spectrometric data; spectral data follow.

#### 2.3.1. Biphenyl (2a) (5)

White solid; M.P. 66–68 °C; Yield: 99%; $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.58 (d, $J$ = 8.2 Hz, 4H), 7.42 (t, $J$ = 8.0 Hz, 4H), 7.32 (t, $J$ = 7.9 Hz, 2H) ppm; $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ 141.2, 128.7, 127.2, 127.1 ppm; MS (EI): 155 (M + 1).

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### Table 1. Comparison of self-coupling reactions of (H)ABAs using transition metal-based catalysts.

| Entry   | Catalyst | Conditions | Yield (%) | E-factor | Remarks                                                                 |
|---------|----------|------------|-----------|----------|-------------------------------------------------------------------------|
| 1       | Ti$_{89}$Pd$_{50}$O$_{1,97}$ (20) | 1.5 eq. K$_2$CO$_3$, 1.5 eq. K$_2$S$_2$O$_7$, 110 °C, Acetone-H$_2$O (3:1), 1.5–4 h | 80–99%    | ~56.9     | Precious Pd-catalyst, heating, 1.5 eq. each of base and oxidant, high temperature and volatile solvents are required. |
| 2       | [Pd(β-OH)Cl(Ph)]$_2$ (22) | KOH, EtOH, reflux, 6 h | 70–99%    | ~10.1     | Precious and expensive Pd-complex as catalyst, non-renewable base, refluxing and large reaction times are necessary. |
| 3       | Pd Colloids (23) | Water–CH$_3$CN (1:1), K$_2$CO$_3$ (2 eq.), 80 °C, 24 h | 40–96%    | ~4.4      | Precious catalyst, problematic solvent, 2 eq. of K$_2$CO$_3$, heating and large reactions are necessary. |
| 4       | Au/chitosan NPs (27) | Water, RT, 1–3 h | 94–99%    | ~3.3      | Precious Au and chitosan based catalyst and limited substrate scope was reported. |
| 5       | [(η^8-benzene)RuCl$_2$(aniline)] (30) | Water, CH$_3$OH, Na$_2$CO$_3$ (2 eq.), Cu(OAc)$_2$ (1.5 eq.), 70 °C, 4–24 h | 36–68%    | ~7.6      | Precious and expensive catalyst, 2 eq. of Na$_2$CO$_3$, 1.5 eq. of Cu(OAc)$_2$, toxic solvent, large reaction times and heating are necessary. |
| 6       | RuCl(PPh$_3$)$_3$ (31) | Water, dioxane, TEMPO, 130 °C, 2 h | 40–82%    | ~10.3     | Precious catalyst, organic solvent, oxidant and high temperature are necessary. |
| 7       | CuO grafted triazine functionalized covalent organic framework (32) | MeOH, 60 °C, 5 h | 59–96%    | ~26.8     | Tedious preparation of catalyst, toxic solvent, heating, limited substrate scope and large reaction time are reported. |
| 8       | [Cu(bpy)$_2$] (33) | iso-PrOH, K$_2$CO$_3$ (1 eq.), RT, 4–15 h | 54–88%    | ~79.3     | Unconventional catalyst, 1 eq. of non-renewable base, large reaction times and limited substrate are reported. |
| 9       | Cu nanoparticles supported on reduced graphene oxide (CuNPs@rGO) (34) | DMF, microwave (360 W) heating, 12–15 min | 86–94%    | ~13.0     | Tedious preparation of catalyst, microwave heating and problematic solvents are required. Limited number of substrates was studied. |
| 10      | [Cu$_2$(trans-cyclohexane-1,2-diamine)$_2$(H$_2$O)$_2$] (OTf)$_2$ (35) | CH$_3$OH, RT, 2–3 h | 40–85%    | ~20.2     | Un-conventional catalyst and toxic solvents are required. Formation of phenols as bi-products and moderate yields are reported. |
| 11      | CuCl (present method) | WEPA, EtOH, RT, 10–45 min | 90–99%    | ~1.25     | Low E-factor, application of waste-derived biorenewable extract, quick reactions, avoid volatile organics, high yields, quick reactions and wide substrate scope. |
2.3.2. 4,4'-Dinitrobiphenyl (2b) (5)
Pale yellow solid; M.P. 235–237 °C; Yield: 99%; 1H NMR (400 MHz, CDCl3): δ 8.37 (d, J = 8.6 Hz, 4H), 7.79 (d, J = 8.6 Hz, 4H) ppm; 13C NMR (100 MHz, CDCl3): δ 148.1, 145.0, 128.4, 124.4 ppm; MS (EI): 245 (M + 1).

2.3.3. 4,4'-Dichlorobiphenyl (2d) (5)
White solid; M.P. 154–156 °C; Yield: 96%; 1H NMR (400 MHz, CDCl3): δ 7.52–7.25 (m, 8H) ppm; 13C NMR (100 MHz, CDCl3): δ 138.5, 133.8, 129.1, 128.3 ppm; MS (EI): 223 (M + 1).

2.3.4. 4,4'-Diformylbiphenyl (2e) (5)
White solid; M.P. 149–151 °C; Yield: 99%; 1H NMR (400 MHz, CDCl3): δ 10.09 (s, 2H), 8.01 (d, J = 8.5 Hz, 4H), 7.80 (d, J = 8.5 Hz, 4H) ppm; 13C NMR (100 MHz, CDCl3): δ 191.7, 145.6, 136.0, 130.4, 128.1 ppm; MS (EI): 211 (M + 1).

2.3.5. 4,4'-Dicarboxamidobiphenyl (2h) (41)
White solid; M.P. 263–265 °C; Yield: 92%; 1H NMR (400 MHz, CDCl3): δ 7.69 (d, J = 8.6 Hz, 4H), 7.60 (d, J = 8.6 Hz, 4H), 6.03 (brs, 2H), 5.77 (brs, 2H) ppm; 13C NMR (100 MHz, CDCl3): δ 168.3, 132.1, 131.9, 129.0, 126.9 ppm; MS (EI): 241 (M + 1).

2.3.6. 3,3'-Dinitrobiphenyl (2i) (42)
Yellow solid; M.P. 201–203 °C; Yield: 98%; 1H NMR (400 MHz, CDCl3): δ 8.51 (t, J = 2.0 Hz, 2H), 8.31 (ddd, J = 2.1, 2.3, 8.2 Hz, 2H), 7.99–7.96 (m, 2H), 7.71 (t, J = 7.9 Hz, 2H) ppm; 13C NMR (100 MHz, CDCl3): δ 148.9, 140.4, 133.1, 130.3, 123.3, 122.2 ppm; MS (EI): 245 (M + 1).

2.3.7. Dimethyl biphenyl-3,3'-dicarboxylate (2k) (5)
White solid; M.P. 343–345 °C; Yield: 97%; 1H NMR (400 MHz, CDCl3): δ 8.31 (s, 2H), 8.05 (d, J = 7.8 Hz, 2H), 7.81 (d, J = 7.7 Hz, 2H), 7.54 (t, J = 7.7 Hz, 2H), 3.96 (s, 6H) ppm; 13C NMR (100 MHz, CDCl3): δ 166.9, 140.4, 131.6, 130.9, 129.0, 128.8, 128.3, 52.3 ppm; MS (EI): 271 (M + 1).

2.3.8. 2,2'-Diacetylbiphenyl (2m) (5)
White solid; M.P. 83–85 °C; Yield: 94%; 1H NMR (400 MHz, CDCl3): δ 7.74 (dd, J = 1.9, 7.6 Hz, 2H), 7.52–7.43 (m, 4H), 7.17 (dd, J = 1.8, 7.8 Hz, 2H), 2.26 (s, 6H) ppm; 13C NMR (100 MHz, CDCl3): δ 201.7, 140.7, 138.7, 131.1, 130.8, 128.6, 127.6, 29.3 ppm; MS (EI): 239 (M + 1).

2.3.9. 4,4'-Methoxybiphenyl (2o) (5)
Colorless solid; M.P. 174–176 °C; Yield: 99%; 1H NMR (400 MHz, CDCl3): δ 7.41 (d, J = 8.7 Hz, 4H), 6.89 (d, J = 8.7 Hz, 4H), 3.77 (s, 6H) ppm; 13C NMR (125 MHz, CDCl3): δ 158.7, 133.5, 127.7, 114.2, 55.3 ppm; MS (EI): 215 (M + 1).

2.3.10. 4,4'-tert-Butylbiphenyl (2p) (5)
Colorless solid; M.P. 126–128°C; Yield: 97%; 1H NMR (400 MHz, CDCl3): δ 7.52 (d, J = 8.6 Hz, 4H), 7.44 (d, J = 8.6 Hz, 4H), 1.35 (s, 18H) ppm; 13C NMR (100 MHz, CDCl3): δ 166.9, 140.4, 131.6, 130.9, 129.0, 128.8, 128.3, 52.3 ppm; MS (EI): 271 (M + 1).

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**Table 2. Optimization studies.a**

| Entry | Catalyst (mol%) | WEPA (mL) | EtOH (mL) | Time (min) | Isolated yield (%) |
|-------|-----------------|-----------|-----------|------------|--------------------|
| 1     | CuCl (2)        | 0.5       |           | 720        | 20                 |
| 2     | CuCl (2)        | 0.5       | 0.5       | 180        | 32                 |
| 3     | CuCl (2)        | 1         | 0.5       | 60         | 39                 |
| 4     | CuCl (3)        | 1         | 0.5       | 60         | 63                 |
| 5     | CuCl (4)        | 1         | 0.5       | 40         | 82                 |
| 6     | CuCl (5)        | 1         | 0.5       | 10         | 99                 |
| 7     | CuCl (6)        | 1         | 0.5       | 10         | 99                 |
| 8     | CuCl (5)        | 2         | 0.5       | 10         | 99                 |
| 9     | CuCl (5)        | –         | 0.5       | 720        | –                  |
| 10    | –                | 1         | 0.5       | 720        | –                  |
| 11    | CuCl (5)        | –         | 0.5       | 150        | 72                 |
| 12    | CuCl (5)        | –         | 0.5       | 60         | 92                 |
| 13    | CuSO4 (5)       | 1         | 0.5       | 720        | –                  |
| 14    | FeCl3 (5)       | 1         | 0.5       | 720        | –                  |
| 15    | Ni(OAc)2 (5)    | 1         | 0.5       | 720        | –                  |
| 16    | NiCl2 (5)       | 1         | 0.5       | 720        | –                  |
| 17    | MnCl2 (5)       | 1         | 0.5       | 720        | –                  |

aReaction conditions: 1 mmol of phenylboronic acid (1a) at RT.
b1 mL of water extract of wood ash (WEWA) was employed.
c1 mL of water extract of banana peel ash (WEB) was used.
CDCl₃): δ 150.0, 138.3, 126.8, 125.7, 34.6, 31.5 ppm; MS (EI): 267 (M + 1).

2.3.11. 5,5′-Difluoro-2,2′-dimethoxybiphenyl (2s) (5)
White solid; M.P. 127–129 °C; Yield: 90%; ¹H NMR (400 MHz, CDCl₃): δ 7.04–6.94 (m, 4H), 6.93–6.84 (m, 2H), 3.74 (s, 6H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ 156.7 (d, J = 237.4 Hz), 153.1 (d, J = 2.0 Hz), 127.9 (d, J = 8.0 Hz), 118.2 (d, J = 23.2 Hz), 114.9 (d, J = 22.5 Hz), 112.2 (d, J = 8.4 Hz), 56.4 ppm; MS (EI): 251 (M + 1).

2.3.12. 3,3′-Dicyano-5,5′-difluorobiphenyl (2t) (5)
White solid; M. P. 230–232 °C; Yield: 92%; ¹H NMR (400 MHz, CDCl₃): δ 7.65 (s, 2H), 7.51 (dt, J = 2.3, 8.9 Hz, 2H), 7.48–7.43 (m, 2H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ 162.7 (d, J = 250.8 Hz), 141.4 (dd, J = 2.8, 7.1 Hz), 126.7 (d, J = 3.6 Hz), 119.4 (d, J = 24.7 Hz), 119.1 (d, J = 22.5 Hz), 116.9 (d, J = 3.0 Hz), 115.1 (d, J = 9.5 Hz) ppm; MS (EI): 241 (M + 1).

Table 3. Self-coupling reactions of (H)ABAs using CuCl in WEPA.

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\begin{array}{cccccc}
\text{1H NMR (400 MHz, CDCl₃)} & \delta & \text{ppm;} & \text{MS (EI):} & \text{1H NMR (400 MHz, CDCl₃)} & \delta & \text{ppm;} \\
\end{array}
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2.3.13. 9,9′-Biphenanthrene (2x) (13)
Colorless solid; M.P. 191–193 °C; Yield: 94%; ¹H NMR (400 MHz, CDCl₃): δ 8.81 (dd, J = 6.5, 7.7 Hz, 4H), 7.92 (d, J = 7.7 Hz, 2H), 7.85 (s, 2H), 7.77–7.60 (m, 6H), 7.50 (d, J = 8.2 Hz, 2H), 7.40–7.33 (m, 2H) ppm; ¹³C NMR (100 MHz, CDCl₃): δ 137.2, 132.2, 131.7, 139.4, 128.8, 128.5, 127.6, 127.0, 126.8, 126.7, 126.2, 122.8, 122.7 ppm; MS (EI): 355 (M + 1).

The copies of ¹H and ¹³C NMR spectra of representative compounds have been provided in supporting information of this article. The structures of compounds 2c, 2f, 2g, 2j, 2l, 2n, 2q, 2r, 2u, 2v, and 2w have been confirmed by the
comparison of the TLC retention factor (Rf) values with authentic samples of our recent reports (5,19).

2.4. E-factor calculation for the self-coupling of phenylboronic acid in WEPA without including the column chromatographic purification of product

The E-factor for the self-coupling of 1.0 mmol of phenylboronic acid (1a) using CuCl (5 mol%) and ethanol (0.5 mL) in WEPA to produce 99% yield of symmetrical biaryl, 2a (Table 2, entry 6): E-factor = {[(0.122 g of 1a + 0.007 g of CuCl + 0.39 g of ethanol + 0.002 g of WEPA (the removal of water of pomegranate peel ash extract provides 2 mg pale yellow material that can be lost after the reaction reaction)) – (0.35 g of ethanol that can be recovered after the reaction at ~90% rate + 0.076 g of biphenyl, 2a)])/0.076 g of biphenyl, 2a = 1.25.

2.5. E-factor calculation for the self-coupling of phenylboronic acid in WEPA by including the column chromatographic separation of product

The E-factor for the self-coupling of 1.0 mmol of phenylboronic acid (1a) to give 99% yield of 2a employing CuCl (5 mol%), and ethanol (0.5 mL) in WEPA followed by the column chromatographic purification of 2a using 9.10 g of silica-gel, 20 mL of n-hexane and 0.2 mL of ethyl acetate (the eluent, n-hexane and ethyl acetate was recovered @ 71% and reused for the column chromatography): E-factor = {[(0.122 g of 1a + 0.007 g of CuCl + 0.39 g of ethanol + 0.002 g of WEPA + 9.10 g of silica-gel + 13.1 g of n-hexane + 0.180 g of ethyl acetate) – (0.35 g of recovered ethanol @ 90% + 0.076 g of biphenyl, 2a + 9.301 g of recovered n-hexane @ 71% + 0.129 g of recovered ethyl acetate @ 71%)]}/0.076 g of biphenyl, 2a = 171.64.

3. Results and discussion

3.1. Characterization of WEPA

Our previous characterization studies on WEPA using XRD, XPS, EDAX, XRF and FTIR displayed that the WEPA consists large quantities of K₂O and KCl, reasonable quantities of SO₃, Na₂O, CaO, MgO, SiO₂ and Al₂O₃ with some other metallic and non-metallic substances in a trace quantities (3–5,13) (please see the supporting information for XPS and XRF data).

3.2. Optimization studies of self-coupling of (H)ABAs

The optimization experiments are shown in Table 2. Initially, 1 mmol of phenylboronic acid (1a) was analyzed for its self-coupling reaction using 0.5 mL of WEPA and 2 mol% of CuCl, and biphenyl (2a) was formed with 20% yield in 12 h at RT (Table 2, entry 1). The addition of 0.5 mL of EtOH as the co-solvent at this stage provided 32% of 2a in 3 h (Table 2, entry 2). The use of 1 mL of WEPA delivered 39% of 2a in 1 h (Table 2, entry 3). The application of 3, 4, 5 and 6 mol% of CuCl gave 63%, 82%, 99% and 99% yields of 2a in 1 h, 40, 10 and 10 min at RT (Table 2, entries 4–7) and these investigations indicate the necessity of 5 mol% of CuCl and 0.5 mL of EtOH for this conversion. The use of 2 mL of WEPA did not show any improvement (Table 2, entries 8), indicating the requirement of 1 mL of WEPA for this self-coupling reaction of 1a. The studies by avoiding WEPA or CuCl showed no reaction (Table 2, entries 9 and 10) indicating the necessity of WEPA and CuCl for this conversion and also show that EtOH acts only as a co-solvent. The model reaction using 1 mL water extract of wood ash (WEWA) (43) and 1 mL water extract of banana ash (WEB) (44) showed 72% and 92% of 2a in 2.5 and 1 h (Table 2, entries 11 and 12), indicating that WEPA is the best amongst them in light of its large amounts of K₂O (Section 3.1) (44). The investigation of self-coupling reactions using other metal-based catalysts such as CuSO₄, FeCl₃, Ni (OAc)₂, NiCl₂ and MnCl₂ showed no reaction (Table 2, entries 13–17) and hence these cannot catalyze the present reaction under WEPA-assisted conditions.

3.3. Substrate scope of self-coupling of (H)ABAs

The challenging substrates such as ABAs; 5-fluoro-2-methoxyphenylboronic acid, 3-fluoro-5-cyanophenylboronic acid and phenanthrene-9-boronic acid, and HABAs; pyridine-3-boronic acid, 2-methylypyridine-3-boronic acid and pyridine-2-boronic acid were also found to be highly reactive under present CuCl-catalyzed self-coupling reactions in WEPA (Table 3, products 2s–2x).

The suitability of the CuCl-catalyzed conditions for a wide variety of ABAs and HABAs is an advantage of this development using waste-originated biorenewable extract, WEPA. The development of environmentally benign protocols or technology can obviously show a great influence on the sustainability of environment and human life (1,45–47). To assist in understanding whether this protocol is better than other protocols where the amounts of silica-gel and eluents are not provided, we have calculated the E-factor of this protocol for the self-coupling reaction of 1a, and the value is found to be 1.25 without including the column chromatographic purification (Section 2.4). Thus, this method is more effective than those reported previously, which
have E-factors between 3.3 and 79.3 (Table 1). However, by including the column chromatographic purification, this protocol shows an E-factor of 171.64 (Section 2.5).

3.4. Plausible mechanism of CuCl-catalyzed self-coupling reaction of (H)ABAs

The advantage of copper in organic synthesis is that the copper can exist in a range of oxidation states from 0 to +3 in its catalytic cycles via a one or two electron process \((48)\). The mechanism of the present method (Scheme 2) has been proposed based on the literature reports \((37, 49)\). Initially, CuIICl participates in oxidative addition \((I)\) with the resultant species \((a)\) formed by the reaction of ABA with the base of WEPA [the base is mostly KOH, since the large quantity of \(K_2O\) (Section 3.1) of WEPA will be transformed readily to KOH in the presence of water \((3–5, 13)\)] to generate intermediary CuII species, \(A\). The intermediate \(A\) reacts further with \(a\) (oxidative addition, \(II\)) to form CuIII intermediate, \(B\), which undergoes reductive elimination \((III)\) in WEPA to produce CuIICl and symmetrical biaryl, \(2\).

4. Conclusions

In summary, a CuCl-catalyzed, low E-factor protocol has been developed for the oxidative self-coupling reaction of (H)ABAs in WEPA at RT by avoiding non-renewable oxidants. WEPA is a waste-originated biorenewable basic media and hence the present strategy is a good example for waste valorisation to the C–C coupling reaction. The present method shows advantages like the use of biorenewable base and reaction media, ambient conditions, quick reaction times, high to nearly quantitative yields, elimination of volatile organic solvents and non-renewable oxidants and high substrate scope. The current CuCl-catalyzed method with mild conditions avoiding additional organics by using waste-derived media may become the most advantageous method for the Cu-assisted self-coupling reactions of (H)ABAs.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Scheme 2. Proposed mechanism of CuCl-catalyzed self-coupling of (H)ABAs in WEPA.
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